Public and Private Benefits of Autonomous Vehicles

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Highlights

Autonomous vehicles (AVs) will provide both public and private benefits. The private benefits motivate individuals to purchase AVs and utilize shared AV services. The public benefits are the basis for public policies to support and accelerate deployment of AVs.

Preliminary estimates are that if AVs could be deployed now in most of the fleet of conventional vehicles, quantifiable benefits could be in the range of $275 to $800 billion per year, after as much as possible eliminating double counting of benefits.

Projections by SAFE assume that the entire fleet of passenger cars and trucks could be replaced with AVs by 2050. Following SAFE's scenarios for deployment over the 32-year period from 2018 to 2050, the discounted present value of AV benefits could be from $3.2 to $6.3 trillion. That is double to four times the $1.5 trillion in value that was created by the Interstate Highway System over the longer 40-year period from 1956 to 1996.

In addition, AVs would improve the quality of life and mental health of as many as 20 million seniors and mobility-limited today, and a larger percentage as the population ages.

Private benefits that motivate new car buyers to purchase AVs include:

- Surveys of new car buyers who are now willing to purchase AVs reveal they would gain a benefit worth over $99 billion per year from the ability to purchase fully autonomous vehicles.

- Bottom up calculations of private benefits from more efficient use of time while in the vehicle suggest even larger benefits, of $182 to $219 billion annually. The benefits of more intensive use of vehicles by family members and need for fewer vehicles for family transportation would be additional.

- Benefits of self-driving taxi and Uber-type services would be $3.9 to $10.6 billion.

- Lower labor costs and fuel savings in heavy-duty trucks would be from $90 billion to $296 billion depending on how extensively AV technology replaces drivers.

The public benefits of AVs that justify policies to accelerate their introduction include:

- Congestion reduction, with a potential value of $71 billion per year from savings in time and fuel.

- Benefits of reduced accidents of $118 to $503 billion per year.

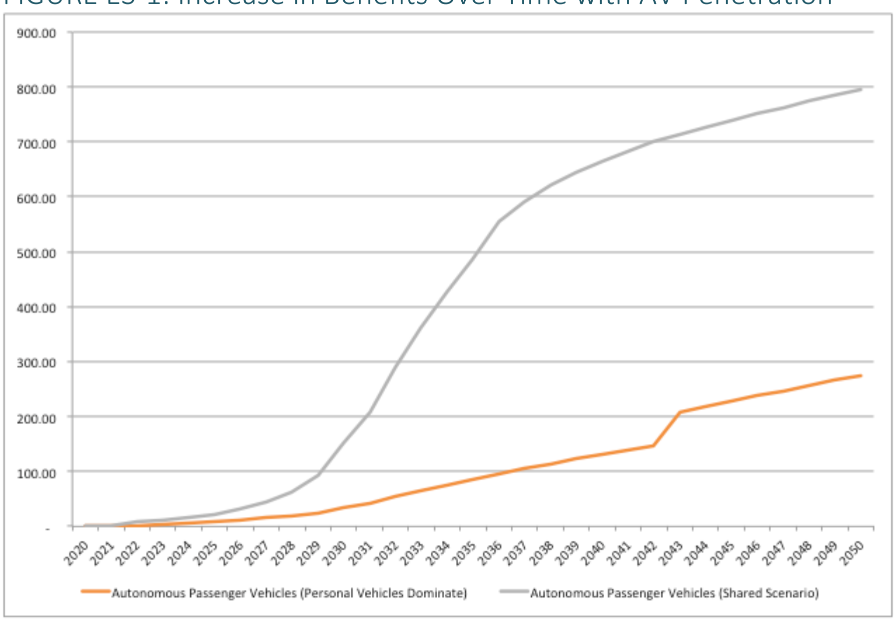
- Energy security and environmental benefits of about $13 to $58 billion per year due to reductions in gasoline and diesel consumption from reduced congestion, platooning and introduction of electric vehicles (EVs) in fleets. These benefits include lower prices for imported oil, reduced risks of oil price spikes and supply disruptions, and lower motor vehicle emissions.

This quantification is based on the assumption that 100 percent of passenger-carrying vehicles are capable of autonomous operation without human operators. Thus, these calculations apply to some future time in which autonomous vehicles have fully replaced the current vehicle parc. It is also assumed that there is no change in personal or freight vehicle miles traveled or total fuel use over time, so that this growth in benefits is solely due to an increase in the percentage of AVs in the vehicle parc. Should vehicle miles traveled (VMT), fuel use and congestion grow over time, benefits in both scenarios would be larger.

Figure ES-1 illustrates how benefits could be expected to grow over time under high and low projections of the rate of penetration and the magnitude of steady-state benefits. In the high case, penetration is more rapid driven by replacement of a large share of new personally-owned vehicles by shared electric vehicles, and ultimately all freight trucks would be self-driven. In addition, the high end of benefits from AVs in passenger cars and trucks is assumed.

In the lower case, AV penetration still reaches 100 percent by 2050 but it is slower and shared vehicles never exceed 16 percent of the fleet. The low end of the range of benefits from complete replacement of passenger vehicles is assumed and only platooning is achieved by automation of freight trucks.

FIGURE ES-1: Increase in Benefits Over Time with AV Penetration



A clear conclusion is that the public benefits that justify government intervention to support AVs are even larger than the private benefits that provide incentives for buyers to purchase AVs. That suggests that far from slowing the introduction of this new technology, the focus of public policy should be on removing barriers to its adoption. This conclusion is reinforced by the public benefits that are difficult to quantify.

Benefits that are harder to quantify include:

- Broader access to job and shopping opportunities due to the combined effects of lessened congestion and more efficient use of time while driving. These improved opportunities would lead to higher earnings as well as lower cost of living from improved ability to find the lowest prices.
    - Based on current average shopping trip distance and speeds, higher speeds and lower congestion would increase the accessible shopping region by 20 percent and increase the area for job search by over 150 percent.

    - The much greater benefit for job search is achieved because commuting is frequently during rush hour and gains much greater benefits in both speed increase and in value of travel time than shopping and other errands that generally occur outside rush hour and with lower valuations of lost time.

- Improved health outcomes for the large segment of the population that receives inadequate medical treatment due to lack of affordable and available transportation.
    - The 2009 NHTS reports that about 20 million people report having a medical condition that makes it hard to travel and because of this medical condition have reduced their day-to-day travel.

    - There are widespread reports that Medicaid's $3 billion non-emergency medical transportation (NEMT) program is broken.

    - Roughly one-third of people with disabilities have no transportation available to them. Most of those with disabilities who do travel do so in private cars. The most significant travel barriers have to do with the pedestrian environment before or after motorized travel

- Many elderly self-regulate their driving because of concern about their driving ability.

Taken together, these findings suggest a major role for AVs, either personally owned for those unable to drive or shared for those who cannot afford their own vehicle.

By eliminating the cost of drivers, AVs would make subsidized taxi service much more affordable and capable of providing longer distance transportation to specialized facilities.

I. Introduction

Autonomous Vehicles (AVs), also referred to as self-driving vehicles, have attracted immense interest. Many new cars are equipped with lane-following, crash avoidance, lane-changing and parking capabilities that operate autonomously once initiated by the driver. Auto companies advertise fully autonomous vehicles to be available in the near future that will take over all driving tasks under specified conditions. Google has publicized its self-driven vehicle and several companies have tested self-driven vehicles under controlled circumstances.

The purpose of this study is to identify the economic benefits that could be achieved through large-scale introduction of AVs. In contrast to studies that address macroeconomic outcomes like employment and investment, this study addresses the question of how users of transportation services will be directly affected by introduction of AVs.[1] To the extent possible, it quantifies these effects as costs or benefits in monetary terms.

Different levels of vehicle automation are possible, ranging from currently available driver assistance to fully autonomous vehicles that require no driver intervention under any circumstances. Likewise, there are several classification schemes to categorize levels of autonomy. To avoid making fine distinctions in estimating benefits, this study assumes that all AVs fall into SAE Level 4 or 5 of self-driven vehicles.[2] When particular benefits are associated with vehicles that require no driver intervention under any circumstances (Level 5) or can also be achieved with self-driven vehicles limited to operation under specified conditions (Level 4), that distinction is noted.

The transition to self-driven vehicles will not take place instantly and AVs may never achieve 100 percent penetration. Some benefits of AVs come with the vehicle itself, such as freeing the driver from the need to control the vehicle and enabling him or her to do other tasks while traveling. Other benefits depend on the penetration of AVs in the fleet, in particular reduction in accidents and congestion.

Benefits that are obtained through ownership of an AV, independent of the number of other AVs that are on the road, are referred to as "private benefits." The concept of private benefits has specific implications in economics, in particular it implies that a vehicle purchaser has all the information and incentives needed to decide whether those benefits are great enough to justify what may be the added cost of vehicle automation.

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[1] Thus, the concept of economic benefits adopted in this study is different from that found in, for example, the U.S. Department of Transportation, Intelligent Transportation Systems Joint Program Office, "Benefits Estimation Framework for Automated Vehicle Operations" www.its.dot.gov/intex.htm Final Report - August 2015 FHWA-JPO-16-229. p. 23 which translates direct benefits into macroeconomic categories such as "work time gained through ability to multi-task while driving" rather than quantifying the value of that free time to the driver directly.

[2] See https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety for discussion of the different automation levels.

Thus, private benefits provide the motivation for AV sales and can be used to predict those sales.

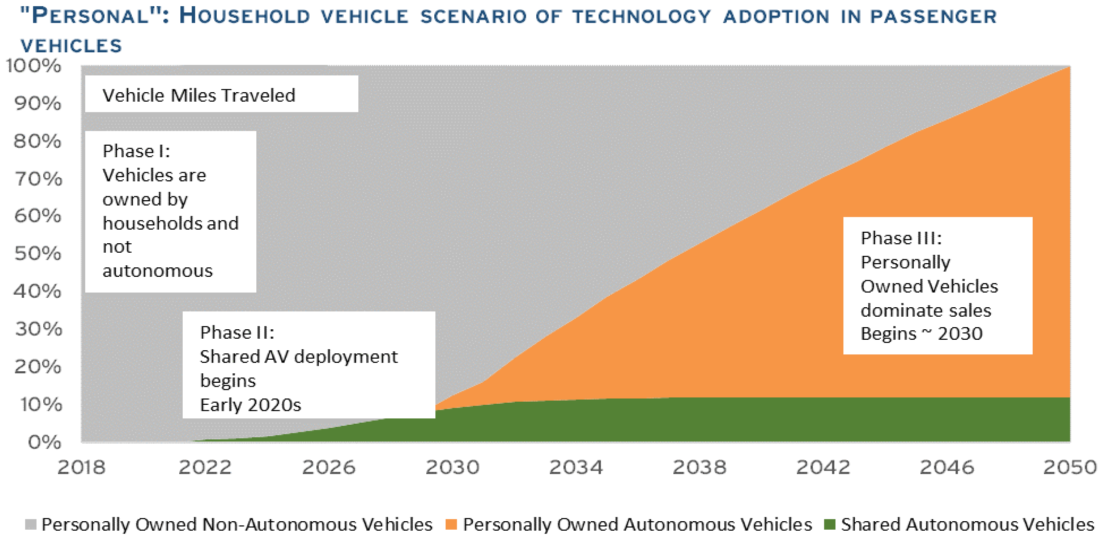
Benefits that are derived from the number of AVs on the road are referred to as "public benefits" or as "externalities." These are benefits that other road users gain from the individual's decision to purchase an AV. These benefits, which may be much larger than private benefits, do not provide an additional incentive for any individual to purchase an AV. Thus, without government intervention of some sort based on the public benefits and externalities of AVs, the penetration of AVs will be slower and ultimately smaller than is socially desirable.

Public benefits may thus be identified with benefits that depend on the percentage of AVs in the vehicles on the road at any given time. This introduces the further complication that some public benefits may grow in proportion to the number of AVs on the road, while others may require that some threshold penetration be achieved before they begin to appear. Reduction in congestion is one of the public benefits for which the question of thresholds is particularly important.

To avoid proliferating distinctions within benefit estimates, this study assumes 100 percent penetration of AVs in its quantification of public benefits. It will be noted in discussion of specific public benefits whether they are likely to be proportional to the penetration of AVs or require some threshold be reached before they appear.

How long it might take for different levels of penetration to appear is therefore a relevant question. For the sake of concreteness, this study assumes when relevant that penetration will follow projections developed by the sponsor, SAFE. The less-aggressive path projected by SAFE is described in Figure I-1. In this scenario shared AV uses peak at 12 percent of miles travelled. It depicts deployment of shared self-driven AVs beginning in 2022 with personally owned vehicle (POV) sales beginning in 2030. To achieve 100 percent penetration by 2050, this scenario assumes that 100 percent of new light duty vehicle sales are AVs from 2030 onwards.

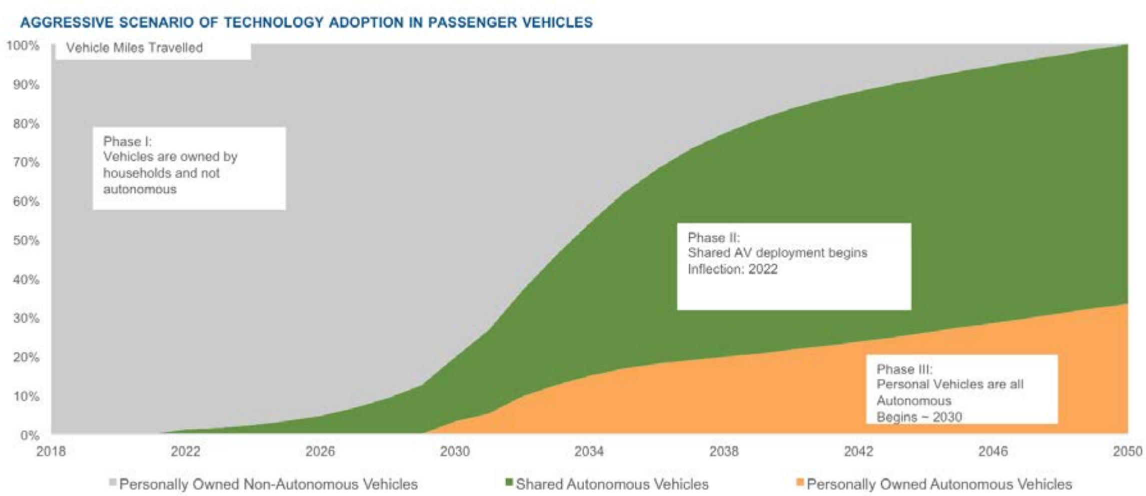
FIGURE I-1: SAFE Household Vehicle Scenario for AV Penetration



Source: Securing America's Energy Future (SAFE)

Figure I-2 shows a more aggressive path in which shared AVs ultimately achieve 67 percent of miles travelled. In this case AVs account for 20 percent of miles travelled in 2030 as opposed to 12.5 percent in the POV case, due to the faster adoption of AVs for shared rides.

FIGURE I-2: SAFE Accelerated AV Penetration Scenario



Source: Securing America's Energy Future (SAFE)

At the end of the report, a projection is made of the rate at which the steady state benefits might be approached, based on these two scenarios.

II. Benefits Framework

The Department of Transportation (DOT) describes several potential benefits of AVs, and these are included in this study:

> "…crash avoidance, reduced energy consumption and vehicle emissions, reduced travel times, improved travel time reliability and multi-modal connections, improved transportation system efficiency and improved accessibility, particularly for persons with disabilities and the growing aging population."[3]

According to DOT,[4] these benefits arise from several potential effects of AVs on the transportation system:

- The reduction of crashes due to human error
- Dramatically improved throughput via reduced vehicle following distances and other improvements in vehicle operations and traffic management
- Improved mobility for those unable or unwilling to drive, and
- Reduced fuel consumption and associated environmental impacts.

Classification of benefits

This study divides benefits into public and private benefits, for the reasons just discussed, and to the extent possible quantifies specific benefits in each of these categories:

1. Private benefits
    a. Value to current vehicle owners
        i. Value to driver of reduced stress and ability to multi-task
        ii. Value of improved utilization of household vehicles
    b. Value of self-driven vehicles to non-drivers who purchase them
    c. Reduced cost of transportation services provided by shared AVs
2. Public benefits
    a. Value of reduced congestion and increased speeds for all travelers
        i. Value of time saved
        ii. Value of fewer traffic accidents
        iii. Value of reduced fuel consumption
        iv. Value of increased access due to lower travel cost
    b. Value of improved access for indigent, handicapped and elderly
        i. Mobility for those without current services
        ii. Lower cost of currently subsidized transportation services for target population
    c. Energy security and air pollution benefits

[3] DOT *ITS Research Fact Sheets - Automated Vehicle Research* (2015) https://www.its.dot.gov/factsheets/AutomationUSDOT.htm

[4] Ibid.

d. Value of larger geographic markets for workers and shoppers

The benefits listed by DOT are largely public benefits. They do not include what this study estimates to be one of the largest categories of benefits, the private benefit to a driver of relief from driving stress and ability to perform other tasks in a self-driven vehicle.

Defining and Estimating Private and Public Benefits

Private benefits of autonomous vehicles will drive their sales and market penetration. Public benefits are the basis for public policy to encourage development and adoption of AVs. Without supportive public policies, market penetration would be limited to sales based solely on private benefits. Appropriate supportive policies could increase penetration of AVs to levels justified by the additional public benefits that AVs provide. Efforts to restrict use of AVs would cause both the private and public benefits of AVs to be foregone.

The public and private economic benefits of autonomous vehicles lend themselves to quantification because in many cases they take the form of lower costs of transportation, in the form of time required or out of pocket expense. Autonomous vehicles can offer other personal and system-wide advantages, some of which—such as reduced accidents—are more straightforward to quantify than others. A solid foundation for benefit estimates is the value of time savings and the reduction in the cost of transportation provided by AVs.

The proper measure of the private economic value of AVs is consumer surplus. The concept of consumer surplus is that consumers in the aggregate gain more from goods they consume than what they pay for them. Consumers surplus answers the question: How much would you be willing to pay for the opportunity to purchase as much of good X as you desired at the going market price? When the good is a new one not now available today in the market, consumers surplus provides the benefit term in a cost benefit analysis of whether or not there will be net benefits to society from developing and producing the good.

Some benefits of AVs fall in the category of public benefits. These are benefits associated with reduced accidents and congestion, that take the form of reduced cost of time spent in travel and out of pocket costs for fuel and accidents. The distinction is that these benefits are provided to all drivers and passengers whether or not they own an AV themselves and increase with the number of AVs on the road. These apply to both shared and POVs.

There is a substantial literature on how without some form of government intervention, it is impossible for the developer of a new good or technology to capture all the consumer surplus in its market price. This is the basis for patent protection, intellectual property laws and government support for research and development.

A positive balance of benefits over cost can also be a justification for taking the effort to remove regulatory barriers or other market failures that slow or prevent development and deployment of new technology.

Importantly, standard macroeconomic impact analysis that looks at jobs and GDP captures little or none of the benefits that are measured by consumer surplus. While the economic efficiencies of reduced freight costs will be reflected in greater output and higher wages, the consumer benefits of AVs largely take the form of improved quality of transportation services—and adjustments to GDP to take into account improved quality are a well-known source of underestimation of benefits of such innovations as personal computing and the Internet, among others.

III. Private benefits

A basic principle behind microeconomic analysis of benefits is if a vehicle purchaser chooses an AV over a comparably or lower priced conventional vehicle, then there is something of value to the buyer that the AV provides and the conventional vehicle does not. Some goods that have very low prices, like water for household use in the U.S., because of their low cost to produce may have immense value to their users. Economists use the concept of willingness to pay for such goods, in contrast to the market price, when quantifying the benefits of, for example, clean water.

WTP estimates for AVs are based on surveys designed to estimate how much various potential buyers would be willing to pay for the opportunity to purchase an AV. For some, this stated preference may include personal valuations and amenities over and above the reduced opportunity cost of driving and will exceed any bottom-up calculation of time and cost savings. For others, including those who enjoy the driving experience or are indifferent to the time saving, the valuation falls below that calculation.

It is important to note that a well-designed WTP survey would include only benefits that an owner/driver/family with a POV would receive personally and directly from owning an AV that they could not enjoy without owning the AV.[5] These are the internalized benefits of AVs.

Shared AVs can also provide benefits in the form of lower transportation cost and greater access to those who do not purchase their own vehicles, but instead use taxis, ride-sharing services or public transportation. These cost-savings can take the form of elimination of the cost of human drivers, better capacity utilization, and shorter wait times for service.

These are also internalized benefits, which accrue to the providers in the form of higher profits (or in the case of public transportation, lower losses) or to the consumer in the form of lower fares and/or better service.

At present, and in a future without AVs, there will be a particular division of users of transportation services into users of POVs and users of shared services. With AVs there may be switching from POV to shared services, due to the lowered cost of shared relative to POV transportation, and also an increase in the use of either or both. The value of increased utilization is also an internalized benefit.

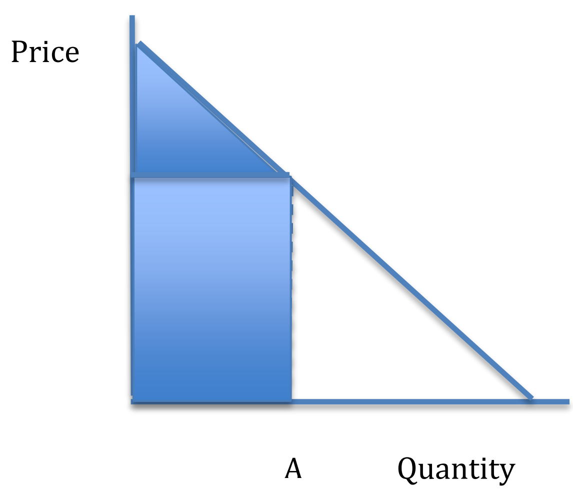
[5] Thus, WTP could be based on a desire to be a first-adopter of new technology, a feeling of doing good for others (helping to reduce congestion and pollution), or other non-monetary rewards as well as measured time and cost savings. It could also be discounted for the enjoyment of the driving experience and will be distributed in light of differing valuation put on time.

Benefits vehicle owners gain from purchasing an AV

Figures I-1 and I-2 illustrate this study's approach to estimating consumer benefits of AVs. The number to be computed is based on the demand curve that plots annual sales of cars and light-duty trucks against their average price. As illustrated in Figure III-1, the aggregate private consumer benefit of introducing some number of AVs, for example A, is the shaded area under the demand curve out to the dashed line at A. The same aggregate benefit will accrue in every year as long as new vehicle sales show no long-term growth or shrinkage over time, as has been the case for number of years. Thus, the present value of introducing AVs over some number of years would be calculated by taking the present value of an income stream whose value in each year is the area up to A.

Consumer surplus is another relevant concept, and it is the aggregate consumer benefit minus the amount that consumers pay for new vehicles. In the figure, consumer surplus generated by AV sales is therefore the upper shaded triangle.

FIGURE III-1: Demand curve and consumer surplus



As Hahn et al point out, it is necessary to have information on the entire demand curve for AVs in order to estimate consumer surplus. Estimates of average willingness to pay are helpful indicators of how much of a cost difference between AVs and conventional vehicles the market will tolerate, but to estimate consumer surplus it is necessary to use the entire demand curve. The same demand curve also gives greater insight into the level of sales and rate of penetration that could be expected at different cost increments.

Willingness to Pay Survey Results

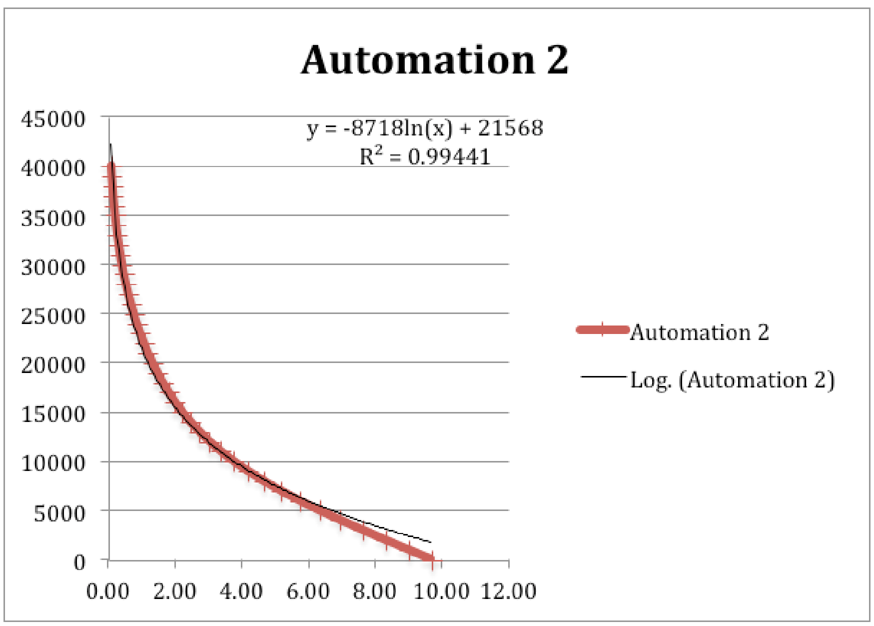
Based on responses of potential buyers to a survey of their willingness to pay a premium for an AV, the benefit of having AVs available is estimated to be $98.5 billion per year.

A paper[6] by Daziano et al. provides a distribution of willingness to pay that provides a suitable basis for constructing a demand curve for AVs. Although there are no other studies of U.S. consumers with the necessary detail, other studies have estimated average willingness to pay for AV and their estimates are consistent with the Daziano et al. study.

Daziano reports a mean willingness to pay for full automation of $4900. A total of 45 percent of Daziano's respondents were unwilling to pay anything extra for an AV and some indicated they would require a discount off conventional vehicles to consider one. For those with positive interest in AVs, the mean willingness to pay for complete automation was between $7000 and $8000 and 5 percent would pay more than $24,000. One other comparable study reports a mean willingness to pay for full automation of $7253.[7]

Appendix A describes how the estimated means and standard deviations of responses to the Daziano study were used to construct Figure III-2. This demand curve plots possible additional costs of AVs in dollars on the vertical axis and the demand for AVs at each cost point on the horizontal axis, and also a curve. The logarithmic curve is a very close fit to the Daziano data except for estimating higher sales at very low prices.

FIGURE III-2: Estimated demand curve for full automation based on Daziano et al.



To calculate aggregate willingness to pay from the demand curve we assign to each group of purchasers a willingness to pay that is the average of the lower bound on that

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[6] Ricardo A. Daziano, 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 78 (2017) 150–164

[7] Bansal, P., Kockelman, K., Singh, A., 2016. *Assessing public opinions of an interest in new vehicle technologies: an Austin perspective*. Transp. Res. Part C.

group's WTP and the WTP of the next higher group. Thus, to the group willing to pay between 0 and 1000 we assign a WTP of 500 and for the group willing to pay between $30,000 and $40,000 we assign a WTP of $35,000.

We then multiply the number of purchasers in each group by the average amount that members of the group are willing to pay. So for the group willing to pay the least, we multiply their average WTP of $500 by the 690,000 members of the group willing to pay between 0 and $1000. Adding these up over all groups we get a total WTP of $98.5 billion.

As an aside, this demand curve implies that if estimated incremental cost were $10,000, there would be sales of 3.8 million fully automated vehicles per year and consumer surplus would be $34 billion.

Bottom Up Construction of Willingness to Pay

It is also possible to build a bottom-up estimate of the private benefit of purchasing an AV based on existing value of travel time (VOTT) studies. This approach yields an annual benefit of $182 billion to $219 billion.

VOTT is used throughout the transportation planning field, and the FHWA has published recommended VOTT default values. These can be differentiated between driver and passenger and between driving in congested and uncongested time periods.

In a study of the economic cost of traffic accidents, NHTSA explains the reasons why increased travel time has a negative value (cost) to travelers:

> The added time spent by vehicle occupants stuck in or detouring around traffic at a crash site is an opportunity cost that represents a real cost to society. While the ability to travel is a valued asset that improves quality-of-life, consumers generally seek to minimize the time spent travelling because it reduces their opportunities to engage in more lucrative or enjoyable pursuits. Time spent travelling could instead be dedicated to production, which would yield monetary benefits to the travelers, their employers, or both. Alternately, it could be spent in recreation or other activities which the traveler would preferably choose to engage in. Finally, the conditions associated with traffic congestion and delay can cause frustration and tension which in themselves have a negative impact on vehicle occupants.[8]

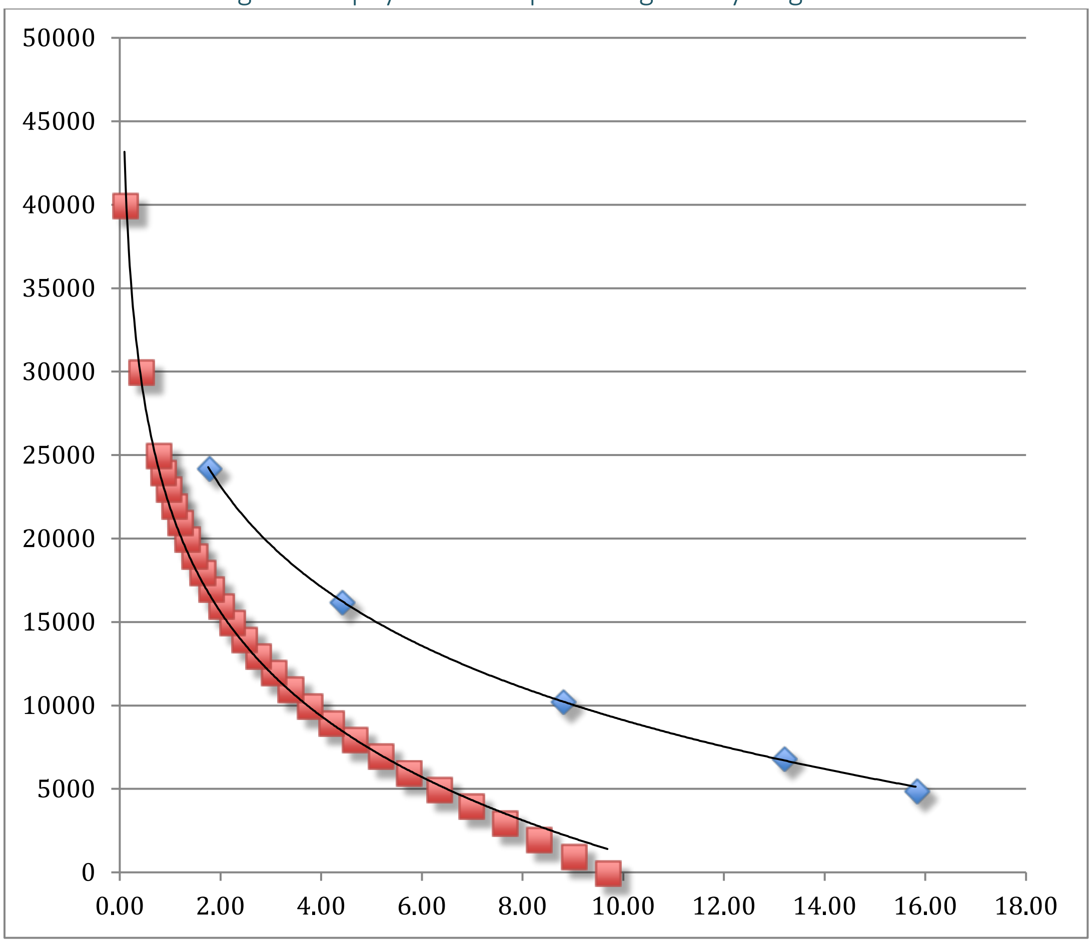
This study uses estimates of the relative travel time values for passengers and drivers under different conditions to put a value on the more efficient time utilization and less

[8] NHTSA: *The Economic and Societal Impact Of Motor Vehicle Crashes*, 2010 (Revised May 2015) p. 102. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812013

stressful experience that a self-driving AV can provide. This, again, is the private benefit that the owner of an AV obtains.

This gives a measure directly comparable to survey results on WTP for an AV. Using prevailing wages for VOTT gives a demand curve that is consistently higher than that derived from stated WTP.

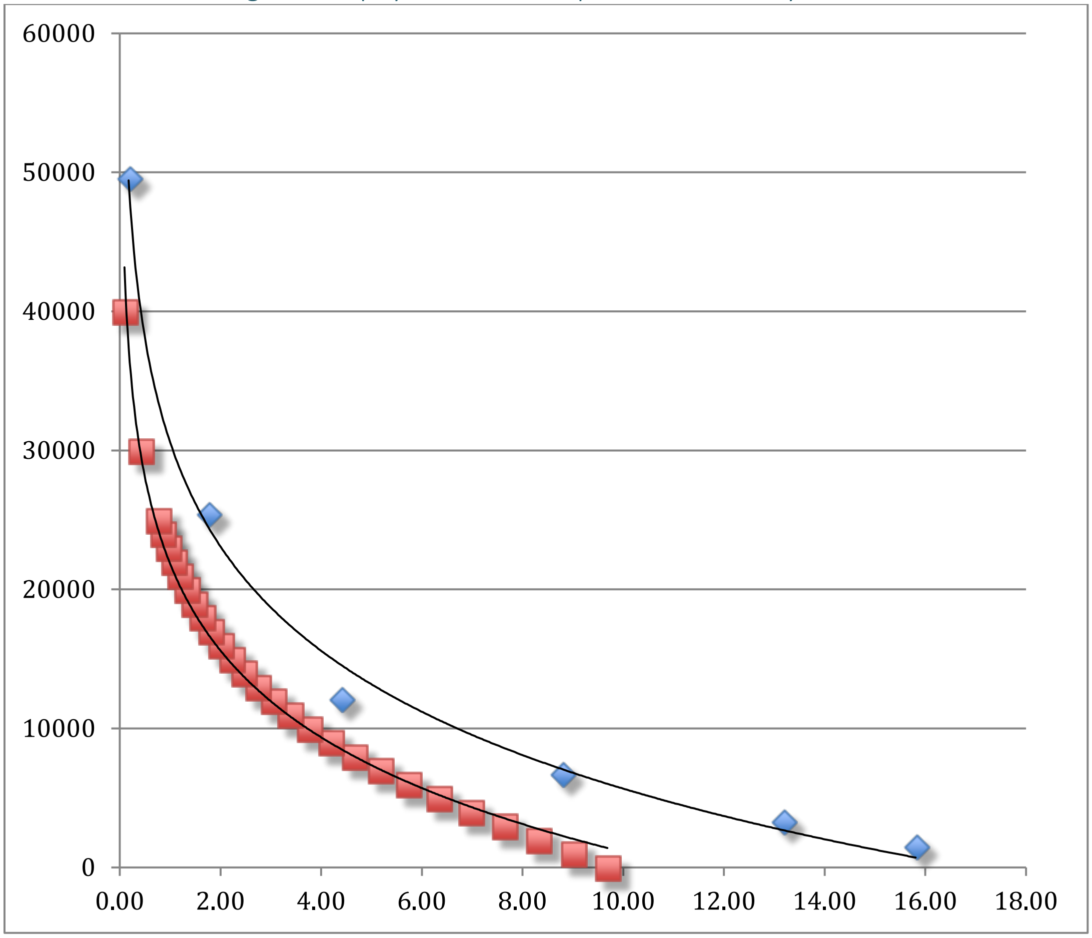
FIGURE III-3 Willingness to pay based on prevailing hourly wage



Using the DOT-recommended 50 percent of annual household income as the VOTT gives a somewhat lower demand curve, but still one with much higher WTP than the curve based on survey responses. Data on the 10th through 99th percentile of household income for 2017 are provided by the U.S. Department of Commerce.[9] Identical calculations to those based on the wage distribution produced a willingness-to-pay curve based on household income, which is shown in Figure III-4.

[9] DQYDJ: *United States Household Income Brackets and Percentiles in 2017* https://dqydj.com/united-states-household-income-brackets-percentiles/

FIGURE III-4: Willingness to pay based on 50 percent of hourly household income



The total reduced cost of travel time implied by the prevailing wage rate and DOT-based VOTT curves is calculated by integrating the area under the fitted logarithmic curves from the first to the 99th percentile of sales.

Based on these three methods of calculation, the overall private benefit to consumers from AVs for personal use by households now purchasing cars is from $99 billion to $219 billion, with a mid-range estimate based on DOT's VOTT methodology of $182 billion. The lower end is based on current stated willingness to pay and the upper end is derived from estimated differences in VOTT for passengers versus drivers under congested and free-flowing conditions using prevailing wage data.

These estimates assume that 100 percent of new AV purchases are POVs. As seen in the projections of AV market penetration discussed earlier, it is expected that a significant share of AVs will be used as shared vehicles,[10] purchased for that purpose.

[10] There is some overlap between the concept of a POV and the concept of a shared vehicle. First, both taxicab and Uber/Lyft drivers also use their vehicles as POV part of the time. Second, sharing within families is classified as personal use even though the household could be seen as running a mini-fleet shared among family members. This is one reason that SAFE divides passenger miles not vehicle ownership

The benefits of adoption of AVs in shared ride services are analyzed in the next section. Although the methodologies used to estimate benefits differ, the two monetary measures can be combined. To avoid double-counting, the total private benefit of adoption of AVs in personal and shared vehicles will be calculated as the weighted average of personal and shared vehicle benefits, with weights taken from the relative shares projected in saturation by SAFE.

Qualifications and Extensions

None of these estimates include the time saving when a driver does not need to search for or transfer from parking to his or her final destination. An AV can take itself to parking, thus saving not only the driver's time but also obtaining lower parking costs.

More efficient use of time is not the only private benefit of self-driving vehicles, as two others are mentioned frequently in discussions of AVs. These are the use of self-driving vehicles to transport members of the household who cannot themselves drive, thus freeing the primary driver from any trip-related cost, and the possibility of eliminating a second (or additional) car when an AV can deliver one family member to a destination then return for another. These important benefits are also left out of these bottom-up calculations of private benefits but should be expected to be included in survey responses about a potential vehicle purchaser's willingness to pay.

One way to reconcile the much larger bottom-up estimates with the WTP estimates from the Daziano survey might be to use the responses of the best-informed group in the Daziano survey as representative of the entire population. This substitution gives a higher WTP curve as depicted below and total benefit of $125 billion, still less than the bottom-up estimates.

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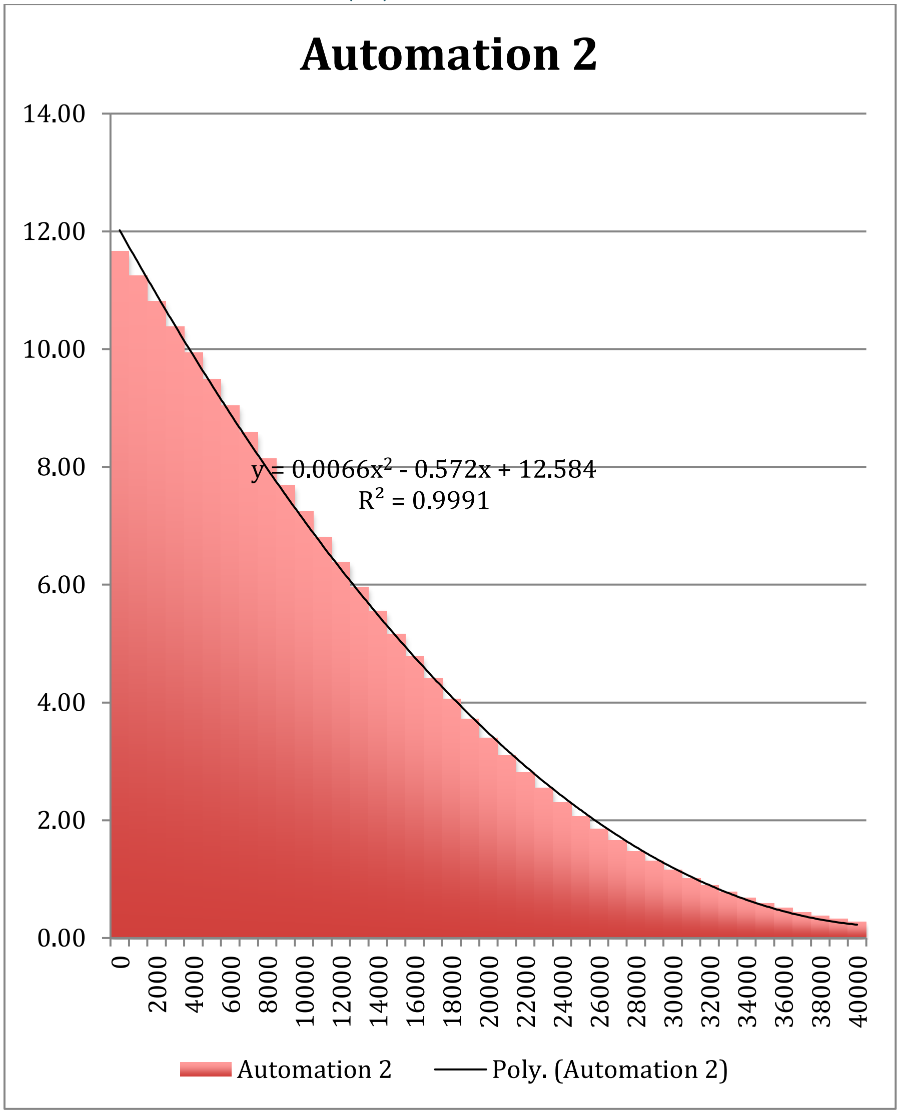
between POV and shared ride services. This lends a bit of fuzziness to the distinction used in this study, which conceptually calls any vehicle not in revenue service a POV and only a vehicle for which the passenger/driver pays a non-family member a shared vehicle. Some vehicles will switch back and forth between these modes.

FIGURE III-5: WTP if entire population is well-informed



These differences between stated preferences and bottom-up calculations of potential benefits are a familiar phenomenon, seen most clearly in the "Conservation Paradox." This is the observation that actual adoption of energy-saving technologies is much slower than engineering calculations of their cost-effectiveness suggest should be the case. It is this phenomenon that gives rise to the use of high discount rates, like the 20 percent chosen in this study to discount future VOTT benefits, in studies of market penetration.

Thus the highest of the bottom-up calculations of time-efficiency benefits of self-driving vehicles suggests that almost 9 million AVs would be purchased with a differential cost of $10,000 while the survey results suggest only half that. It may be that greater familiarity with the technology will lead to more favorable opinions than those of buyers who are well-informed about the current status of AVs, or that technology development will eliminate the cost differential. Nevertheless, this analysis strongly suggests that for AVs to attain 100 percent of new vehicle sales considerably stronger incentives will be required.

Benefits appropriated by users or providers of shared rides

The dollar benefits of providing shared rides with AVs derive largely from eliminating the cost of a driver, which constitutes 50–66 percent of taxi fares. The estimated range of benefits is $3.9 to $10.6 billion per year. In addition, some 20 million persons with limitations on their mobility due to age, health or disability could have much or all of their freedom of movement restored.

The analysis thus far has dealt only with personally owned vehicles. In fact, there is great interest among providers of shared ride services in adopting self-driving vehicles in order to save on labor costs and expand their market.

Conventional licensed taxicabs, Uber and Lyft provide one form of shared ride services in which a driver and vehicle are hired together by the passenger. Zipcar-style vehicle providers as well as conventional rental cars provide a different kind of shared service, in which the vehicle is part of a fleet and driven by the user.

AVs offer significant advantages to providers and users of shared ride services. Cost savings are fundamental, and this study provides estimates of the potential benefits of reducing the cost of currently available shared ride services. The lower fares that could accompany a lower cost structure would attract more customers for shared rides, as well as providing a dollar savings to current users.

Zipcar and rental services would become indistinguishable from other shared ride services, except possibly in how services are contracted and paid for. Since these services would become available to all consumers of transportation services, whether or not they could drive, their market would be significantly expanded.

Moreover, use of Zipcar-style services and conventional rental cars would become much more convenient because the vehicles could be delivered directly to the user, rather than made available in fixed locations.

These effects of the AV technology are therefore likely to cause significant changes in the structure and organization of taxi and rental car industries, with current users of taxis shifting to rental cars and possible users of taxis shifting to rental car services.

Estimation of benefits of AVs for shared services

For the purposes of this study, all these variations in providing shared ride services are lumped together as they are in the SAFE projections. It will be assumed that the costs of all shared services will be reduced by adoption of self-driving vehicles in the same amount as taxi services. The price of rental car services must match the savings in taxi services, or consumers will switch from one to the other until costs-per-mile equalize, since with self-driven vehicles the distinction between the two from a passenger's point of view vanish.

A final point has to do with the sharing of labor cost savings between providers and consumers of shared ride services. In a perfectly competitive industry, the sharing of benefits depends on the relative elasticities of supply and demand. If entry and exit from the shared ride business is very easy, then most of the benefits will go to consumers. If demand grows rapidly, in particular because of the improved access of non-drivers to self-driving vehicles, and supply does not respond as rapidly, most of the cost-savings will become higher profits for providers. Both increased profits and lower consumer cost are benefits, and therefore the estimates provided in this study do not depend on how they are divided between consumers and providers.

What matters is that the cost savings from AVs in shared service are fully appropriated by either consumers or providers. Consumers are motivated by the lower cost to demand shared rides provided by self-driven vehicles and providers of shared rides are motivated by competition to choose self-driven vehicles when they provide comparable services at lower cost than vehicles with drivers.

Thus the cost savings that self-driven vehicles promise for shared ride services would provide an incentive for purchase of AVs in some number without further government intervention. As in the case of POVs, that incentive may not be great enough to achieve all the public benefits of AVs in shared uses so that additional incentives would be required to achieve socially optimal penetration.

Cost savings are fundamental

Cost savings from shared, autonomous vehicles come in three forms: elimination of driver cost, increased capacity utilization, and improved service. Of these, the amount by which capacity utilization could increase is hard to predict, since Uber does not seem to have much higher utilization than hailed taxis, despite its sophisticated communication network. That service of some types of shared rides, especially rental cars, will improve is very clear, because of increased access for non-drivers and delivery to the user's location.

In this study, it is assumed that reduction in the cost of taxi services from elimination of the driver applies to all forms of shared services, because with self-driven vehicles the distinction between taxis and rental cars becomes very blurred. Thus in a sense the reduction in cost of taxi service is used as a proxy for the improvement in the quality of rental car service.

Reduction in the cost of shared ride services can be expected to increase their utilization, both by diverting drivers from POVs to shared rides and by providing access to those who do not now use either POVs or shared rides. This increase in utilization and its contribution to consumer benefits can be estimated using the demand elasticities of Hahn et al. The increase in demand could lead to a higher ratio of revenue service to deadheading or to more vehicles being purchased or both, and actual results are likely to be specific to individual markets. However, comparing Uber's utilization to that of New York taxicabs shows no significant change in the ratio. Thus it is assumed in estimating cost savings that the allocation of vehicle purchase costs to passenger-miles does not change when self-driven vehicles are adopted.

This requires the additional assumption that improved utilization of the fleet just offsets the (unknown) incremental cost of AVs compared to conventional shared vehicles, so that labor cost savings translate directly into cost of service changes no matter how demand changes.

Potential shift to EVs

AVs are expected to have higher utilization rates, both as POVs and as shared or fleet vehicles, than vehicles that require a driver. Higher utilization makes electric vehicles with higher initial costs and lower operating cost more economic, so that for many shared applications electric vehicles would be purchased instead of vehicles with internal combustion engines (ICE). SAFE has developed projections of shared vehicle penetration that reach respectively 16 percent and 61 percent of passenger miles traveled. Today almost all shared vehicles are fueled with gasoline and replacing them with EVs could reduce gasoline consumption proportionally to the shift in VMT.

Whether or not this saving in gasoline consumption would be a net cost saving depends on the future comparison between the added purchase cost of an EV and the lower operating cost. To avoid biasing estimates of benefits of AVs in shared applications, it is assumed that these two cost factors just balance so that EVs there is neither a net private cost nor a net private benefit from substituting electric for gasoline power in shared vehicles.

Benefits to users of taxi and related services

Data on taxi transportation are much sparser than that on other forms of transportation, likely due to the diverse and localized nature of taxi ownership. By combining sources, enough key facts can be established to obtain a rough estimate of the savings that self-driving vehicles could offer.

The New York Taxi and Limousine Commission (NYTLC) published a fact book with useful information about average fares, trip lengths and net versus gross driver income. Since it also reports that New York's fares are about average, it is not unreasonable to extrapolate from New York to total U.S. taxi travel.

A rule of thumb for taxi income is that the driver keeps about 66 percent of the fares and tips he collects, which might be as low as 50 percent if the driver pays for fuel. Comparing gross and net revenue data from the NYTLC yields approximately the same ratio of driver compensation to total fares. The non-driver portion includes lease payments (or depreciation) for vehicles as well as maintenance and insurance costs.

This suggests that AVs could reduce taxi fares by at least half and as much as two-thirds. Greater savings would be possible if vehicle costs could be reduced through more efficient design and utilization of the shared vehicle fleet. Some analysts have speculated that centrally owned fleets might maintain a variety of vehicle types that could be matched to needs of users, for example by substituting a variety of types of purpose-built vehicles for one-size-fits-all taxis. Other possibilities are more efficient central scheduling of fleets of vehicles and the adoption of EVs that could be more economical with the annual miles driven by taxis.

With that range of possible unit cost savings, the next step is to estimate what current expenditures on taxis are. The U.S. Department of Commerce publishes data on taxi and limousine employment and labor compensation,[11] which shows total employment of 77,491 in 2015 and total compensation of $2.45 billion. This implies an average income per driver of $31,653.

Other sources suggest considerable larger expenditures,[12] based on average annual earnings per driver of $24,300 and a total of 239,900 drivers. These numbers imply total driver income of $5.8 billion which, based on a 66 percent driver share, implies total taxi and limousine revenues of $8.8 billion.

Another approach to estimation is to use the number of 890 million trips annually from Census data and apply the New York City average fare of $13.40 and trip length of 2.6 miles to calculate approximately $11 billion in revenue.

If all the savings of eliminating drivers are passed on to riders, and driver compensation is between half and two-thirds of taxi revenue, this implies a saving of $6.6 billion for the largest estimate of revenue and savings and $2.5 billion if the smallest estimate is correct. Both these estimates assume no increase in ridership.

[11] U.S. Census Bureau https://www.census.gov/data/tables/2015/econ/susb/2015-susb-annual.html
[12] Statistic Brain, Taxi Cab Industry Statistics https://www.statisticbrain.com/taxi-cab-statistics/

A detailed analysis of Uber's data on its clearing prices and ridership estimated the elasticity of demand for shared services to be between 0.4 and 0.6.[13] This means that if the price of a trip declines by 10 percent, demand will increase between 4 percent and 6 percent.

Using the mid-point of 0.5 implies that a 66 percent reduction in fares would produce a 33 percent increase in ridership. The benefits gained by these new users, measured as consumer surplus, plus the benefit of lower expenditures for riders already using taxis, would be $4 billion with the higher estimate of total taxi use and $1.4 billion with the lower estimate.

Even though the most reliable census data supports the smaller number, the likely number of self-employed taxi drivers not reported as company employees makes the larger estimate more likely to be representative of taxi and limousine service as a whole, especially as Uber and Lyft with contract drivers substitute for traditional taxi service.

How these cost savings are divided between consumers and providers of taxi and other shared vehicle services is not entirely clear. In the past, the taxi industry has been highly competitive, with easy entry as long as there is open access to scheduling and matching. Uber and Lyft have demonstrated how fast alternative scheduling systems can be deployed to compete with established companies. There might be advantages to having a single, open access scheduling system for taxis as was discussed above for the case of Zipcar-style and rental-type vehicles. It is in this area that rents might be taken by a monopoly provider of scheduling, but thus far independent taxi associations that process requests and broadcast them to affiliated drivers have been sufficient for the current level of service. None of these possible improvements over the status quo are assumed in these benefit estimates, which are based on data from current experience.

With a large number of competing providers of AV fleets, the communication and matching network might become a public utility, since there would be clear returns to scale from having a single matching system. The analogy would be a system like that used by regional electricity transmission operators,[14] which take bids from drivers as well offering demand-responsive prices to riders.

Or search services like Expedia and Travelocity that now search for low hotel and air fares could appear to direct riders to systems with the best fares at any given time.

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[13] Peter Cohen, Robert Hahn, Jonathan Hall, Steven Levitt, Robert Metcalfe *Using Big Data To Estimate Consumer Surplus: The Case Of Uber* Working Paper 22627 http://www.nber.org/papers/w22627 National Bureau Of Economic Research, September 2016

[14] Independent electricity generators offer supplies into an electronic market run by the Independent System Operator or Regional Transmission Organization (ISO/RTO) and electric utilities serving retail customers bid for supplies. The RTO matches bids and offers and sets a market clearing price, much like Uber, but does so as a nonprofit entity serving independent buyers and sellers.

Lower costs and greater convenience in the shared use of self-driven vehicles would also increase the demand for such services. This could include rental or Zipcar-type operations, but estimation of how much the cost and convenience of such operations could be improved by substitution of self-driven vehicles requires a much more detailed analysis of the logistics and cost structure of those businesses.

If the same elasticities were used for these shared rides as for taxis, a straightforward calculation leads to the conclusion that a 25 percent drop in the quality-adjusted cost of shared rides would increase utilization by 15 percent. The standard formula for the benefit of such an increase is that the consumer gains one-half of the increase in demand times the drop in price, and the provider gains the new lower price times the increase in demand minus the cost of providing the additional service.

Benefits for those with impaired mobility

Those who cannot now drive themselves due to poverty or infirmities could benefit from use of self-driving vehicles either as their personal vehicles or for shared rides. Although shared ride services now exist that could in principle be extended to all the mobility impaired even if there were no self-driving vehicles, the lower cost of ride services in self-driven vehicles could make a critical difference in their availability to the mobility impaired.

Both drivers and non-drivers are affected. According to the 2009 National Household Travel Survey, about 9 million non-drivers have a medical condition that affects their mobility and of these, about 8 million have reduced their daily travel. Even more drivers are affected, with about 14.7 million having a medical condition that affects their ability to drive and because of such conditions, 11.7 million have reduced their daily travel. This adds up to over 20 million whose mobility is reduced because of medical conditions of some kind.[15]

Mobility impairment and income

Inadequate access to medical care is an issue that has received considerable attention in the public health literature, particularly for those whose income is inadequate to pay for taxis or other forms of personalized transportation.

A survey conducted in Cleveland, Ohio in 2001 found that almost one-third of respondents at or below 125 percent of the federal poverty level reported that it was “hard” or “very hard” to find transportation to their health care providers. A 1997 survey of cancer patients in Texas found transportation was a major barrier to treatment for 38

[15] Imran Cronk *The Transportation Barrier*, The Atlantic, 2015 https://www.theatlantic.com/health/archive/2015/08/the-transportation-barrier/399728/

percent of white, 55 percent of African American and 60 percent of Hispanic survey respondents.[16]

To cite more recent studies, a review published in 2013 found that approximately 25 percent of lower-income patients missed or rescheduled medical appointments due to lack of transportation. Patients who had problems with transportation missed filling prescriptions more than twice as often as patients without transportation problems.[17]

The link between income and problems with transportation for the disabled was confirmed in broader studies. One cites findings of a 2004 NOD-Harris Interactive poll that almost two-thirds of those with disabilities who reported major transportation problems had annual incomes below $35,000. Transportation problems declined rapidly as income increased and in higher income groups transportation problems were about the same for disabled and non-disabled people.

Inadequacy of existing mass and community transit programs

An interesting 2012 survey found that availability of transportation by car was significantly superior to bus service in providing access to medical care. It reported that low income patients who traveled by car were twice as likely to keep appointments as those who traveled by bus. This suggests an important role for self-driving cars in improving medical access.

Barriers to mobility and how AVs would lower them

Surveys show that most trips by disabled persons for medical treatment are by car and relatively few of the disabled use any alternative mode of transportation, including ADA or specialized paratransit.

The reasons for this strong preference for travel by car are not entirely clear. One possibility is the lack of public transit, since roughly one-third of respondents to one major survey said there was no public transportation available to them. But even when transit was available, three-fourths of the respondents reported that they did not use it. Interestingly, only 16 percent reported that their impairment or health problem prevented them from using public transit. Most of the travel by those with disabilities was in private cars. [18]

The problems most frequently reported by disabled respondents were in the pedestrian environments that they had to traverse to get to transportation or from the

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[16] ibid.

[17] Sandra Rosenbloom *"Transportation Patterns and Problems of People with Disabilities"* National Academy of Sciences, The Future of Disability in America, Appendix G, Committee on Disability in America, Marilyn J. Field and Alan M. Jette, Editors. http://www.nap.edu/catalog/11898.html

[18] Rosenbloom, p. 525

transportation service to their destination.[19] This also suggests self-driving vehicles that provide door-to-door service would be a potential remedy.

Automobile transportation, either as a driver or a rider, was clearly the preferred mode of travel for trips for medical treatment. The same survey reported that almost 90 percent of respondents used a personal vehicle to travel to medical appointments. Despite the subsidies provided for paratransit and accommodations for the disabled in public transportation, less than 4 percent took public buses and less than 2 percent used ADA paratransit.

Access to automobile transportation was also closely associated with employment for the disabled. Over 80 percent of disabled with jobs used a private vehicle to commute to work, half the time in vehicles driven by others. Far fewer than 10 percent used any form of public transportation or specialized transportation for the disabled. The heightened mobility provided to disabled persons by access to was confirmed by other questions in the survey. In response to questions about whether those with disabilities needed help with or had trouble getting transportation, about 14 percent of working age respondents and 32 percent of the elderly answered yes. Having no car, having no available public transportation, or having no one to drive them were the most frequently cited reasons.[20]

Finally, even those with their own automobiles reported voluntary restrictions on their driving that reduced their mobility:

> "Among those with disabilities roughly two-thirds drive less in bad weather and less than they used to; over half avoid rush hour driving, busy roads and intersections, and night driving. Over a third avoid long distance driving, freeways, and unfamiliar places, roughly a fourth drive slower than the speed limit, and more than one in ten avoid left-turns."[21]

These restrictions would be unnecessary with autonomous vehicles. Rosenbloom comments that "There is substantial evidence that the final loss of the ability to drive has a significant emotional component, above and beyond mobility losses," and that the psychological impact of losing the ability to drive has been linked to severe depression and suicide. AV's would alleviate these impacts of aging by allowing the elderly and disabled to continue to enjoy the same mobility and ease of travel as they did when they were younger or not disabled.

Examples of how AVs could benefit the mobility impaired

These are true stories but the names are invented.

[19] Ibid. p. 526
[20] Rosenbloom, p. 526
[21] Ibid. p. 527

Julie's lack of access to medical care

Julie is a woman in her thirties who lives in a town about 50 miles from Knoxville, TN. She has multiple health conditions, including severe heart disease and an inoperable brain tumor. As a consequence of several strokes following open heart surgery, Julie has no use of her legs and can only get around in a wheel chair.

She requires frequent medical monitoring and doctor visits, including weekly blood draws and examinations at hospitals in Knoxville and Nashville. The hospitals are respectively 50 and 250 miles from her home. Taxi service is infeasible because of the cost of an unoccupied return trip by the taxi after drop-off. A wide network shared vehicle system would not only lower the one-way cost but would put the vehicle back in revenue service immediately after delivering Julie to the hospital or back home.

Julie owns a car that she drove until her strokes made driving impossible. It now sits in the driveway of her mother's house where she lives.

At this time, Julie has no transportation options. She cannot even get to a store to buy food for her dog and car, groceries or other necessities for herself, or materials for the blankets that she makes for terminally ill children in local hospitals. In the last three months, she has missed several critically important examinations to determine the progression of cancer in her brain and to monitor and treat her heart disease.

There is no shared ride service in the town where Julie lives, and taxis are beyond her means for frequent trips in town and for the distances to hospital where her complex conditions can be treated.

If the car sitting outside Julie's house were even a Level 4 AV, her critical needs would be fully met. The same would be true if self-driving vehicles led to shared ride services becoming available over wider areas not now served.

In either case, Julie could be seated in the car with available assistance and travel to her medical appointments where assistance with mobility outside the vehicle would be available.

As Julie's condition progresses, she will need more specialized vehicle services including the ability to enter and exit the vehicle without leaving her wheelchair. There are designs of personally owned Level 5 vehicles that have automated wheelchair lifts, since there is no need for even a single occupant to have vehicle controls.

Unfortunately, Julie is unable to pay for a new vehicle, even if all the autonomous and assistance features were free. Shared ride services would be ideal for her, as long as the fleets of shared vehicles included ones with adequate assistance services to allow her to enter. The savings possible with intensively used fleets not requiring drivers would put this kind of mobility within her financial reach, with the financial assistance that she is currently receiving from friends.

John's intellectual challenges

John is a 75-year-old male with good physical health but limited short term memory. He needs supervision because he tends to wander and forget where he is. He frightened everyone the last time he tried to drive by himself, because he took his grandchildren for a ride and could not remember where he lived or how to get home. Paradoxically, John is able to enjoy normal activities and plays golf regularly. He keeps trying to get out on his own, but even driving down a quarter-mile lane to his mailbox can leave him puzzled about where he is and why he is driving.

The mobility issue also affects his wife, who has less ability to continue her own formerly active social life because she has to transport John to everything that he does.

A personally owned or shared autonomous vehicle would suit the needs of this family perfectly. It would enable Judy to have time of her own, and enable John to drive to golf, accompany his grandchildren on drives, and do simple errands. The most important feature needed by Judy would be ability to lock in a route and destination so that John would have neither the need nor the ability to control the vehicle. The entire family would have mobility that is not now attainable and freedom from worry about what might happen if John found the keys and tried to go somewhere.

Helene's knee surgery

Helene had knee surgery and is not allowed to drive for six weeks. Since week two of her convalescence, she has been paying $100 per day, three days a week, for a helper to drive her to medical appointments, physical therapy and for shopping and other personal errands. That adds up to $1200 for the four weeks of assisted transportation.

Her helper drives 15 miles on her own each way to pick Esther up and return her home, adding to fuel consumption and congestion.

If Helene's POV were an AV, all these costs would be eliminated. She could get into the vehicle, program in her destinations, and avoid all restrictions on her mobility. Her access would actually improve because she would not feel obliged to ration her trips to those worth the cost of her helper's added time.

Quantification of benefits to mobility challenged

The surveys described in this section suggest several conclusions about the scale of benefits that self-driving vehicles could provide to the elderly and disabled. Including drivers and non-drivers, about 20 million have medical conditions that reduce their mobility with current transportation options.
For as many as one-third of those with impaired mobility, public transportation is not an option, but even when it is, only a small percentage make use of it.

The nine million non-drivers face substantially greater difficulties getting needed transportation for medical care or other purposes than those who can drive themselves. Door-to-door service in paratransit or by personal vehicle would be the most beneficial option for them, because of the difficulties that those reporting problems with transportation have in navigating pedestrian environments.

Elderly drivers with reduced confidence in their driving would benefit from self-driving vehicles, and the correlation between employment and ability to drive suggests that job opportunities would expand for those with disabilities if they had access to self-driving vehicles.

Even with subsidized paratransit and public mass transportation, lower-income patients face much more difficulty in gaining access to medical treatment.

Self-driving vehicles to provide enhanced and more cost-effective transportation options for the needy, and access to shared or personally owned autonomous vehicles could improve mobility for all those with medical conditions and handicaps that make travel difficult.

In particular, all studies agree on the inadequacy of current paratransit options. [22] Labor costs are a very large fraction of operating costs for all public systems, [23] so that considerably more services could be provided with the same budget if paratransit were provided by self-driving vehicles. Some of the savings could also be devoted to improving service quality, in particular use of passenger cars dispatched directly and immediately to the mobility impaired in place of multiple passenger vans with longer wait times and service intervals.

Trucking

Users of light-duty vehicles will not be the only beneficiaries of AV technology and likely not the soonest. Demonstrations of the application of AVs to long distance trucking are

[22] Rosenbloom, p. 553.
[23] Based on data in 2016 Report Year Federal Transit Administration U.S. Department of Transportation Office of Budget and Policy September 2017, Transit Profiles: 2016 Full Reporters

already underway. Several states have passed legislation to facilitate these demonstrations on public roads. For long distance trucking, a widely discussed application of AV technology is to form convoys of tractor-trailer rigs. These convoys would initially have drivers in each cab, but with speed and distance between trucks controlled from the lead vehicle. This command, control and communication system would allow trucks safely to "draft" each other much like racing cars, and the resulting reduction in aerodynamic drag is estimated to reduce fuel consumption by about 20 percent.

The next major cost saving would come from eliminating drivers in all but the lead vehicle, turning the convoy into a rubber-tire equivalent of a freight train. Depending on what turns out to be the optimal length of a convoy, this would at least halve labor costs for trucking with a two-truck convoy and by 75 percent with a four-truck convoy.

A hidden cost of freight transportation is the investment in inventory that is in transit on trucks. Reductions in congestion would increase average speeds and reduce the time that a given shipment is on a truck. This is another external benefit of the introduction of AVs into the light duty vehicles that account for 85 percent of VMT as well as commercial trucks. If the average shipping time were reduced by, say, 5 percent the result would be that 5 percent less inventory would be tied sitting in trailers. The effects on productivity would be of the same kind as the benefits of Just-In-Time inventory management that have been achieved by many manufacturers in the past 25 years.

All of these benefits in freight transportation lend themselves to quantification. A number of studies have used simulation models and experiments with truck convoys to come up with the estimate of a 10–15 percent saving in fuel consumption in platoons.[24] If all combination trucks, which account for 38 percent of total truck miles were platooned, this would be a saving of or approximately 900 million to 1.3 billion gallons of diesel fuel. At current prices that is a saving of $1.6 to $2.4 billion dollars.

Statistics on labor costs as a fraction of total variable costs for highway transportation are available from the American Trucking Association.[25] With lower fuel costs in 2017, these data imply that labor costs are 44 percent of motor carrier costs per mile. In 2016 freight transportation revenues were $696 billion. [26] Assuming a 15 percent margin, labor costs of 44 percent of motor carrier costs equate to total freight truck operator compensation of $296 billion.

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[24] Chu, Jennifer, "Driverless Platoons" http://news.mit.edu/2016/driverless-truck-platoons-save-time-fuel-1221 December 20, 2016

[25] Dan Murray W. Ford Torrey, IV "An Analysis of the Operational Costs of Trucking: 2014 Update" September 2014 American Transportation Research Institute

[26] American Trucking Associations, "ATA American Trucking Trends 2017" http://www.trucking.org/article/ATA-American-Trucking-Trends-2017

Combination trucks accounted for 38 percent of total freight truck miles in 2014,[27] and assuming that all those combination truck miles could be done in convoys of 5 automated trucks with a single driver, total motor carrier costs could be reduced by 13 percent. This cost reduction would total $90 billion annually.

The cost saving could be up to $296 billion (44 percent of revenues after eliminating a 15 percent profit margin) if all freight drivers were replaced with CAV.

Getting even a ballpark estimate of the savings in inventory cost achievable with higher freight speeds would be a more challenging study. Data on the total value of shipments are available but they would need to be combined with data on the distribution of delivery times broken into highway and non-highway time requirements. Increasing average highway speeds will not reduce freight delivery times proportionally, because of the time required for local movements and loading and unloading of freight.

There has been considerable research on how improvements in freight transportation have improved productivity economy-wide and in particular on how reductions in the cost of freight transportation translate into higher GDP. The consistent finding is that cost-savings in transportation have a multiplier effect throughout the rest of the economy,[28] so that the net increase in GDP and in demand for workers would be at least twice the cost reduction in transportation.

[27] American Trucking Associations, "Industry Data" http://www.trucking.org/News_and_Information_Reports_Industry_Data.aspx

[28] FHWA Measuring the Impacts of Freight Transportation Improvements on the Economy and Competitiveness https://ops.fhwa.dot.gov/publications/fhwahop15034/ch4.htm

IV. External benefits

Three of the quantifiable external benefits of AVs are addressed in this study:

- Reduction in accidents which avoids the associated medical and repair costs and also contributes to reducing congestion
- Reduction in congestion and higher average speeds, which reduces the time cost of travel
- Lower fuel consumption due reduced congestion and to the choice of electric vehicles in fleets of shared use vehicles

Accidents themselves are a significant contributor to congestion. In addition, research on traffic behavior has shown that anticipation of accidents also has an effect on congestion. Since they expect accidents to occur more frequently under congested conditions, drivers adopt additional safety measures, such as wider vehicle spacing and slower speeds, which further slow traffic when they encounter congestion.

Thus the ability of AVs to avoid accidents removes a direct cause of congestion and also the behavioral changes that make congestion worse. Put another way, road capacity is reduced over the course of a year by the occurrence of accidents and by the choices drivers make about safe headways and speeds. Road capacity will be increased by AVs because they would reduce the frequency of accidents and would also be driven with reduced headways and at higher speeds without increasing accident rates.

I use data on the percentage of accidents attributable to human error and the percentage of congestion due to accidents to estimate the reduction in accidents due to AVs.

Indeed, the ability of AVs to coordinate vehicle movements and avoid human error serves simultaneously to prevent accidents and to reduce congestion. Reduced congestion and higher average speeds are achieved in several ways. Due to their ability to communicate and react more quickly to information, AVs can violate rules of thumb like “two seconds separation” without increasing accident risk. Due to their ability synchronize changes in speed, AVs can also maintain steady traffic flow with constant spacing between vehicles at higher speeds and avoid accordion-like flows. Through communication with each other or a central dispatcher, AVs can coordinate lane changes and movements through intersections to avoid sudden deceleration and queues. These capabilities of AVs increase the capacity of roadways so that traffic flows that would cause congestion with conventional vehicles can move freely when self-driven.

To estimate how much AVs could reduce congestion I use data on the percentage of congestion attributed to accidents and credit AVs with eliminating these delays. I then use a simple model like those in the Australian paper to estimate how much reduced headways and increased speeds could increase road capacity.

Finally, I apply the VOTT values developed earlier in this report to put a dollar value on the reduction in congestion.

Congestion

Although it is not known for certain what percentage of AVs are required in the fleet to reduce congestion, ultimately the congestion benefit of AVs could reach $71 billion.

The Texas A&M Transportation Institute (TTI) issues a comprehensive report on traffic congestion every few years. In its most recent report, for 2015, it estimated that 26 percent of trips encounter severe or extreme congestion. Those 26 percent of trips accounted for 80 percent of the lost travel time due to congestion.

TTI estimated that in 2015 congestion wasted a total of 6.9 billion hours of driving and 3.1 billion gallons of fuel, for a cost of $120 Billion. Many of the causes of congestion could be alleviated or eliminated by use of autonomous vehicles with peer to peer connections or centrally operated traffic flow optimization.

Time savings

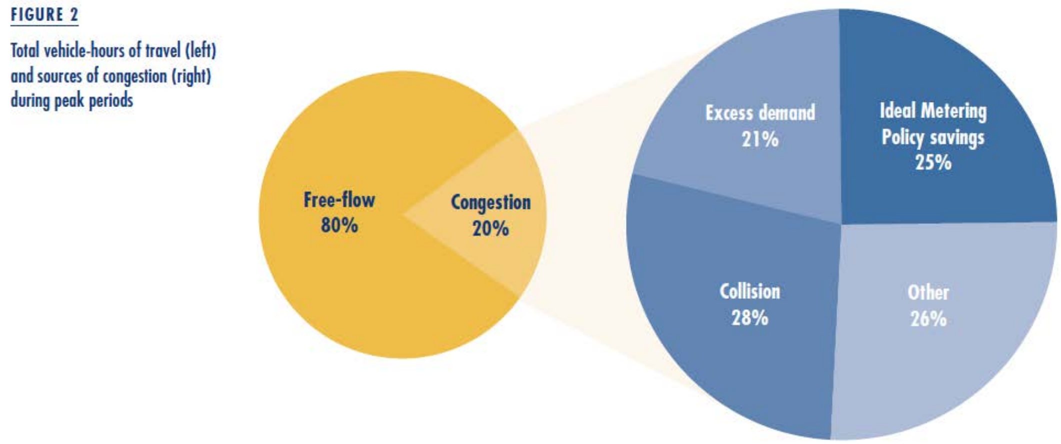
Congestion occurs when the capacity of the road system is exceeded. The immediate cause could be saturation, due to an increase in the number of vehicles using a particular link or a reduction in the capacity of the link. Conditions that impede the smooth flow of traffic such as traffic lights, lane changes, and rubber-necking can also cause or exacerbate congestion even when traffic is below saturation levels.

Some types of congestion occur regularly and predictably: routes to summer resorts that flow freely during the week become congested at predictable times on weekends and routes that flow freely outside rush hours become congested during those daily commuting times.

Another study[29] provides additional insight into the causes of congestion. Figure IV-1 below, copied from that study, estimates that 20 percent of vehicle hours are spent in congested conditions. This is smaller than the estimate by TTI but of similar magnitude. The more interesting findings have to do with allocating the hours among causes of congestion.

[29] Pravin Varaiya: *What We've Learned About Highway Congestion* Access No. 27, Fall 2005

FIGURE IV-1: Causes of Congestion

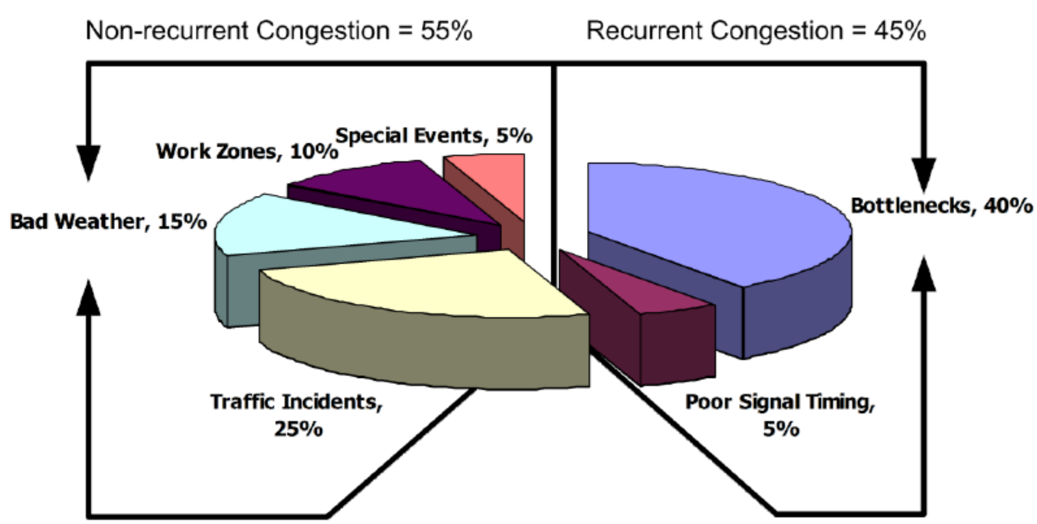


Source: Variaya 2005

Excess demand is responsible for 21 percent and interrupted traffic flow, due to merging vehicles, intersections and similar causes, is responsible for another 25 percent. This 46 percent of congestion could be addressed by autonomous vehicles.

Another breakdown of the causes of congestion is provided by TTI.

FIGURE IV-2: Causes of non-recurrent and recurrent congestion



Source: Beverly Kuhn EFFICIENT USE OF HIGHWAY CAPACITY SUMMARY FHWA-HOP-10-023 Texas A&M Transportation Institute May 2010

Roadworks and other intentional lane closures also cause predictable congestion. These planned events create congestion both by decreasing capacity of a road or bridge and by interrupting smooth traffic flow as drivers merge into fewer lanes in an imperfectly coordinated fashion.

Traffic lights will predictably create queues at intersections during heavy traffic flow periods even if they are programmed to respond to traffic flow, or lack thereof, in different directions.

Accidents are the major cause of randomly occurring traffic congestion, though accidents also tend to be more prevalent during periods of saturation. Accidents cause congestion both by reducing capacity of the network when lanes are blocked and by causing rubbernecking and speed changes when vehicles pass the accident. The effects of accidents on congestion are taken up in the next section and will not be included in the estimates of this section.

Reducing congestion by increasing capacity

Bottlenecks, or congestion caused by more vehicles trying to use a road segment than its capacity. Therefore, increasing capacity of those segments can alleviate congestion. AVs have the capability of multiplying capacity by factors of two or more.

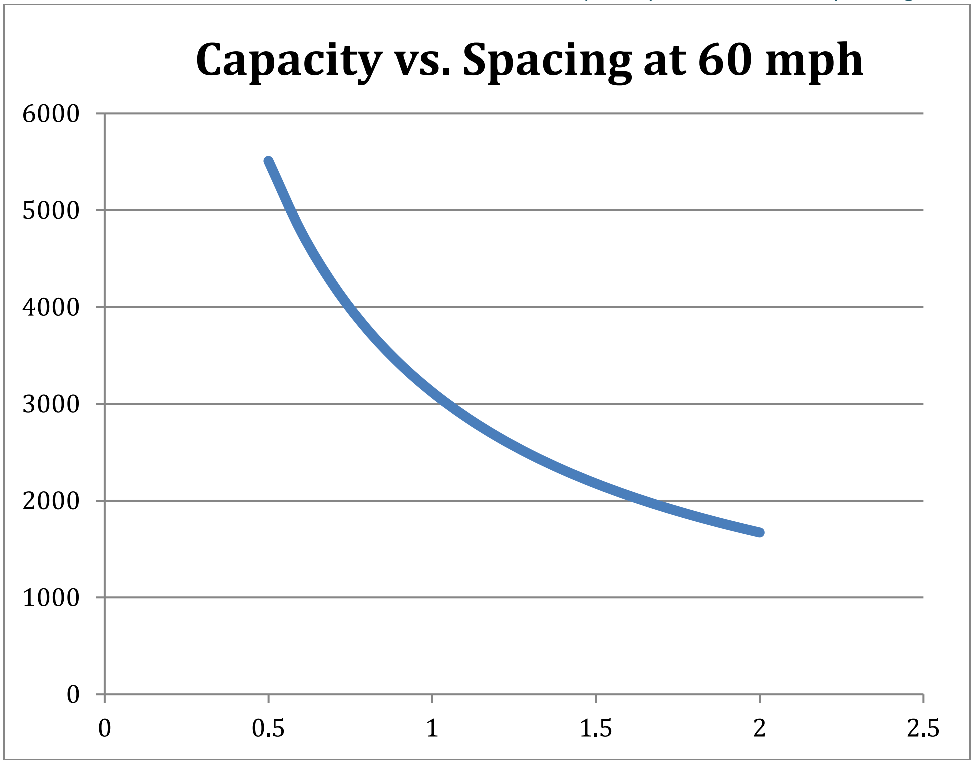
There is a rule of thumb that if drivers maintain safe distances between vehicles at all speeds the maximum capacity of any traffic lane is 2000 vehicles per hour. That is because at speeds above about 50 mph and average car lengths, the space occupied by a vehicle plus the safe interval between it and the next vehicle increase at the same rate as vehicle speed.[30]

Of course, it is possible to pack vehicles together more closely than one car length for every 10 miles per hour, but that will not happen if drivers decide to maintain the same time or distance between vehicles. Moreover, closer spacing combined with human reaction times and driver error lead to an increasing probability of accidents at worst and of accordion effects that reduce average speeds and traffic flow. The communication that is possible between AVs as well as their faster and more reliable responses to unexpected speed changes makes tighter packing feasible.

Figure IV-3 shows a simple calculation of the theoretical relationship between spacing in seconds and capacity at a speed of 60 mph. Whereas increasing speeds with constant 2 second intervals cannot exceed a maximum capacity of about 2000 vehicles per hour, moving from two-second to 0.5-second spacing can increase capacity by a factor of three.

[30] Anthony Downs *Still Stuck in Traffic: Coping with Peak-Hour Traffic Congestion* Brookings Institution Press, 2005

FIGURE IV-3: Theoretical relation between capacity and vehicle spacing



Everyone has experienced the phenomenon of coming to a dead stop on an apparently unobstructed freeway when a chain reaction of rapid braking is followed by a lag in acceleration back to the highway speed. This chain reaction can be caused by a vehicle driving below the speed limit on an uncrowded highway as well as by sudden lane changes or other disturbances to smooth traffic flow.

Since lack of capacity relative to travel demand is the underlying cause of predictable congestion, both the regular type that occurs during rush hours and the sporadic type from land closures and road work, one way to quantify the potential effect of AVs on congestion is to estimate how much AVs could increase road capacity.

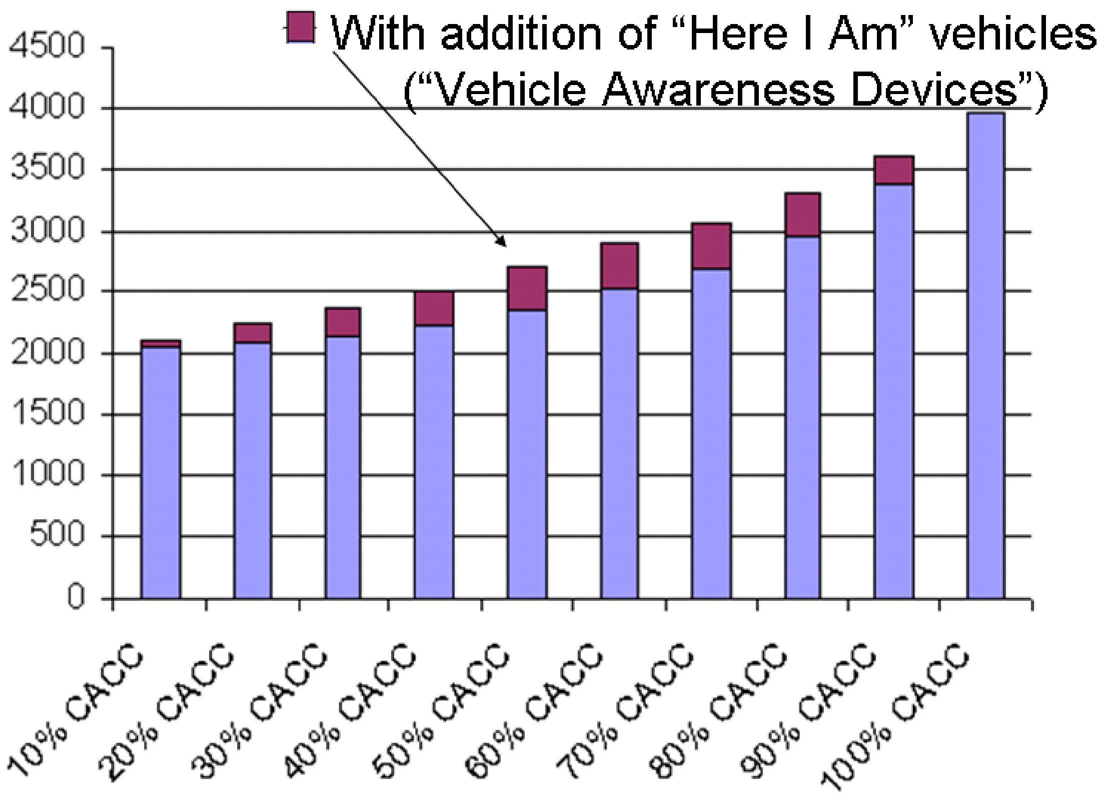
Human factors are eliminated by fully autonomous vehicles, either in peer-to-peer or centrally-controlled modes. By communicating changes in speed or lanes from leading vehicles, autonomous vehicles can anticipate speed changes and avoid the rapid braking and lagging acceleration that causes accordion effects. Likewise, peer-to-peer communication can smooth lane changes to minimize effects of bottlenecks.[31]

[31] American Highway Users Alliance *"Unclogging America's Arteries: 2015 Prescriptions for Healthier Highways"* https://www.highways.org/wp-content/uploads/2015/11/unclogging-study2015-hi-res.pdf

With peer-to-peer communication and faster-than-human reaction times, AVs can also travel with closer spacing without increased likelihood of accidents. Cutting vehicle spacing to half the distances considered safe for human drivers would double highway capacity on routes not interrupted by traffic lights or other external disturbances of traffic flow.

Several much more sophisticated modeling studies reach the same conclusion. A study by Shladover et al. finds that capacity increases linearly with market penetration of vehicles capable of cooperating in speed adjustments, with a 50 percent improvement in capacity at 70 percent penetration.[32]

FIGURE IV-4: Capacity increases due to AV speed cooperation



Source: Shladover et al. 2012

[32] Steven E. Shladover, Dongyan Su, Xiao-Yun Lu *"Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow"* January 2012 Transportation Research Record Journal of the Transportation Research Board. Similar findings by Julian Laufer *"Freeway capacity, saturation flow and the car following behavioral algorithm of the VISSIM microsimulation"* Software Discussion in 30th Australasian Transport Research Forum

> "These results showed a maximum lane capacity of about 4000 vehicles per hour if all vehicles were equipped with CACC. If the vehicle population consists of Cooperative Adaptive Cruise Control (CACC) and Vehicle Awareness Devices (VAD) vehicles, the lane capacity increases approximately linearly from 2000 to 4000 as the percentage of CACC vehicles increases from zero to one hundred. On the other hand, if the vehicle population consists of manual and CACC vehicles, without any mandate for non-CACC vehicles to be equipped with DSRC, the increase in lane capacity follows a quadratic profile, lagging significantly behind at the intermediate market penetration values. Therefore, the capacity benefits of CACC can be accelerated, or obtained at somewhat lower market penetrations, if the rest of the vehicle population is equipped with Vehicle Awareness Devices so that they can serve as the lead vehicles for the CACC vehicles."[33]

Another study that analyzed the formation of "shockwaves" of sudden slowing of traffic propagated from single vehicle speed changes found similar results, with rapid increases in capacity when AVs reach 50 percent market penetration.[34]

FIGURE IV-5: Relation between AV market penetration and capacity

Market Penetration of Equipped Vehicles	Total Through Volume (veh/mi/ln)
Base	2,424
20%	2,287
40%	2,276
60%	3,192
80%	3,585
100%	3,952

Source: Shelton et al TTI

A third laboratory experiment found even more encouraging results, that having 1 car in 10 able to anticipate and compensate for speed change incidents could smooth traffic flow.[35]

[33] Schladover et al 2012

[34] Jeff Shelton, Swapnil Samant, Jason Wagner, Ginger Goodin, Ed Seymour, and Tim Lomax, *Revolutionizing Our Roadways Modeling the Traffic Impacts from Automated and Connected Vehicles in a Complex, Congested Urban Setting* by Texas A&M Transportation Institute

[35] Raphael E. Stern et al "*Dissipation of stop-and-go waves via control of autonomous vehicles: Field experiments*" https://arxiv.org/abs/1705.01693

Estimated benefits of time savings from reduced bottlenecks

There is a clear understanding that AVs can substantially reduce congestion by increasing road capacity, and some agreement that a 50–70 percent penetration of AVs into the on-road fleet would provide as much as a 50-percent increase in capacity.

If this were sufficient to alleviate the "bottleneck" congestion described by Kuhn as responsible for 40 percent of total congestion, a reduction of 40 percent in the $120 billion congestion cost estimated by TTI would save $48 billion.

Reduction in congestion through better timing

Peer-to-peer or central communication can also reroute vehicles optimally. The maximum throughput of a network with several alternative routes is achieved when all are moving at their optimal speed. The problem with current communication systems for rerouting, like WIND, is that they are not predictive and so can overload alternative routes if all drivers respond to the recommendations simultaneously. AVs could be signaled selectively to take alternative routes with centralized communication and traffic optimization, thus equalizing time to destination across all the alternative routes. Moreover, the central traffic controller could take into account known and predictable future congestion so as to avoid loading up routes that will naturally become more congested while the rerouted vehicles are being sent to them.

In a fully automated system, traffic light and merging delays could be minimized in two ways. The accordion effects of those interruptions to smooth traffic flow would be reduced by peer-to-peer communication that allowed all vehicles to move at optimal speeds toward the choke points. The choke points themselves could be modified by replacing traffic lights by a slot-based system that assigned each vehicle a time and speed to cross an intersection and eliminated queueing for a light to change.

Estimation of time savings from improved timing

Figure IV-2 shows an estimate that 5 percent of congestion is due to poor vehicle timing. If AVs made it possible to achieve optimal flow through intersections and merges, elimination of that form of congestion would provide a proportional reduction of the $120 billion estimated annual cost of congestion. Eliminating poor vehicle timing would eliminate 5 percent of that cost and provide a benefit of $6 billion annually.

The problem of induced demand

Several analysts have expressed concern that as traffic moves faster and the time cost of travel falls, there will be a take-back effect that will restore congestion to prior levels. Simulation of the effects of dead-heading of personally-owned AVs have shown that it is possible that gasoline consumption could increase for that reason. It should be noted that this would only happen if the added convenience and more efficient utilization of the household's fleet of vehicles would make the increased gasoline expense worthwhile. And if it does, it would on balance be a good thing.

It is also unlikely that demand for travel would increase sufficiently due to lower travel costs to offset the reduction in congestion, for two reasons. First, estimates of the demand elasticity for either shared rides or vehicle miles traveled (VMT) are relatively low—likely less than a 4 percent increase in VMT for a 10 percent reduction in variable cost per mile. Second, if there were much of a takeback effect due to reduced congestion, additional driving would restore congested conditions and raise the cost of driving back to a level that choked off the increase.

Finally, the introduction of AVs would be a structural change in the nature of travel demand. There is a linkage between private willingness to pay for AVs and their public benefit of reducing congestion. The unpleasantness of driving in congested conditions makes that 20 percent of miles travelled responsible for 33 percent of the value of an AV to the buyer. If congestion be erased, buyers would be marginally less motivated to buy AVs. However, neither this reduced incentive nor the shorter travel times provided by reduced congestion could possibly be sufficient to wipe out all congestion improvements. If they did, the incentive to drive more would disappear and the incentive to buy an AV to multitask would be restored. Thus at most there will be some moderation of the public benefits of AVs associated with reducing fuel consumption and congestion. But the magnitude of improvements in road capacity possible with AVs would make it very hard to bring back current levels of congestion given the low elasticity of VMT demand with respect to cost of travel.

Accident damage

Based on a study by NHTSA for accident costs, AVs could reduce those costs by $118 to $503 billion if all accidents clearly attributable to driver error or incapacity were eliminated.

A 2010 report by the National Highway Traffic Safety Administration (NHTSA) analyzed the causes and costs of traffic accidents in great detail.[36] NHTSA estimated economic costs of traffic accidents in 2010 to be $242 billion, and when quality of life costs are added, the damage rises to $836 billion. Economic costs in the NHTSA study include medical care, legal costs, emergency services, insurance administrative costs, workplace costs, congestion impacts, and property damage. Quality of life includes the value of a statistical life (VSL) for fatal injuries and pain and suffering, represented by the value of Quality Adjusted Life Years (QALY)[37], for nonfatal injuries.

[36] National Highway Traffic Safety Administration (NHTSA) *The Economic and Societal Impact Of Motor Vehicle Crashes*, 2010(Revised) DOT HS 812 013 May 2015 (Revised)

[37] See https://ods.od.nih.gov/pubs/economicanalysis2010/Miller.pdf for a discussion of VSL and QALY.

Although there are many controversies about how the value of a statistical life and the value of quality adjusted life years are measured, the comprehensive cost estimate is more conceptually consistent with the consumer surplus framework adopted in this report than the pure economic cost. It dwarfs in magnitude all the other potential benefits of AVs.

Reduction in accidents by self-driving vehicles

NHTSA separates out numerous causes of traffic accidents, most of which involve some form of driver choice, error or incapacity. The most important factors discussed by NHTSA that might be reduced by self-driving vehicles are distraction, alcohol and excessive speed. Although an AV could be programmed to remain stationary until all occupants are buckled in, the same could be done with current vehicles. Helmet non-use only applies to motorcycles which do not yet appear in the agendas of companies trying out AV technology.

TABLE IV-1: Summary of accident causes and cost

	Economic Cost (Millions of 2010 Dollars)	percent Total	Comprehensive Cost (Millions of 2010 Dollars)	percent Total
Adverse Driver Behavior:				
Seat Belt Non-use	$10,435	4.30 percent	$68,600	8.20 percent
Helmet non-use	$1,215	0.50 percent	$7,592	0.90 percent
Distraction	$39,700	16.40 percent	$123,390	14.80 percent
Alcohol Causation	$43,154	17.80 percent	$193,642	23.20 percent
Speed	$51,964	21.50 percent	$203,228	24.30 percent
Total for distraction, alcohol and speed	$134,818	56 percent	$520,260	62 percent

Source: NHTSA 2010

Estimate of direct benefits

Even with those exclusions and the accidents for which NHTSA did not know the cause, AVs could in principle eliminate 56 percent of the hard economic costs and 62 percent of the pain and suffering costs of traffic accidents. This adds up to $135 billion in economic cost savings and $520 billion in comprehensive damages.

Estimate of indirect congestion benefits

NHTSA estimates the cost of congestion due to traffic accidents to be $28 billion in 2010 or 12 percent of total economic costs.[38] This is about 23 percent of the TTI estimate of congestion costs of $120 billion in 2010, though NHTSA warns against making this comparison due to differences in methodology and a cost per vehicle hour of delay in the NHTSA study about 14 percent greater than that used by TTI. Adjusting for that difference would make congestion costs caused by traffic accidents about 20 percent of total congestion costs.

Since estimates for reduction in congestion costs thus far include congestion caused by lack of capacity and by faulty timing of vehicle interactions, the reduction in accidents would provide an additional congestion benefit not yet accounted for.

It can be assumed that of the $28 billion that NHTSA attributes to traffic accidents, the fraction attributable to distraction, alcohol and speed could be avoided with AVs. The reduction that eliminating these cases would make in NHTSA's economic cost of accidents is 56 percent. If this reduction is applied to the 25 percent of congestion costs that TTI attributes to accidents, the reduction in congestion cost would 56 percent of 25 percent of the damages attributed to accidents. This is an additional saving of 14 percent of $120 billion or $17 billion in value of travel time saved. As a check, 56 percent of NHTSA's $28 billion cost of congestion caused by accidents is $16 billion.

Once these cost savings are switched to the congestion category, NHTSA's comprehensive cost of traffic accidents would have to be reduced from $520 billion to $503 billion and its economic cost from $135 to $118 billion.

Qualifications and additional questions

Since the adverse driver behaviors are all voluntary, a serious question is whether drivers who adopt these behaviors when they are behind the wheel would succumb to the temptation to take over control of an AV to continue them. The fact that AVs allow all occupants of the vehicle to multitask while travelling should eliminate the problem of distraction and associated accident damage. Intoxication with alcohol (or other drugs) and habitual speeding might be more recalcitrant. To the extent that alcohol impairs judgement, an intoxicated driver might fail or refuse to relinquish control of the AV. Even more likely, a driver who speeds when in control of the vehicle is likely to be frustrated by the autonomous speed choices of a self-driven vehicle. By definition, a Level 4 AV will allow the driver to take control, and to be 100 percent effective in controlling behavior a Level 5 vehicle would have to be built with no controls that the driver could operate.

Such vehicles might be a very hard sell. Hacking of Level 5 vehicles to allow driver control could become a large industry, but drivers not interested in relinquishing control have a much simpler solution. It is likely that people who engage in these risky behaviors would

[38] NHTSA 2010, p. 110.

have a low or negative willingness to pay for an AV and would purchase a conventional vehicle instead.

Thus as long as freedom to choose between conventional and autonomous vehicles or to take control of an autonomous vehicle is maintained, it is difficult to predict how much AVs would reduce traffic accidents. It does seem likely that accident reduction, to whatever extent it occurs, would be proportional to the penetration of AVs into the fleet since every instance of drinking, distraction or speeding that is eliminated will reduce the probability of accidents.

Energy security benefits

Reduced fuel use

There is considerable debate about whether and by how much the introduction of AVs will reduce consumption of gasoline. The fundamental relationship that governs the answer is a version of the Kaya Identity: Gasoline consumption equals VMT times fuel efficiency (gallons per mile traveled). There is little doubt that autonomous vehicles will reduce gallons per mile travelled (or liters/100 km), but also concern that adoption of autonomous vehicles will lead to more miles being travelled, possibly by a large enough margin to make gasoline consumption increase.

Fuel savings in POV

There are two main reasons why introduction of autonomous vehicles would improve fuel efficiency of personal vehicles. One is reduced congestion. Reduced congestion takes away the penalty that frequent acceleration and braking, together with time spent idling, apply to fuel efficiency. This could save approximately 80,000 barrels per day of gasoline consumption, applying the percentage reduction in congestion estimated above to the TTI estimate of fuel wasted due to congestion.

The second reason is that autonomous vehicles are expected to have higher utilization rates, both as personally operated vehicles and as shared or fleet vehicles, than vehicles that require a driver. Higher utilization makes EVs with higher initial costs and lower operating cost more economic, so that for many shared applications electric vehicles would be purchased instead of vehicles with internal combustion engines (ICE). SAFE has developed projections of shared vehicle penetration that reach respectively 12.5 percent and 67.5 percent of passenger miles traveled. Today almost all shared vehicles are fueled with gasoline and replacing them with EVs could reduce gasoline consumption proportionally to the shift in VMT.

There are also several reasons why these decreases in fuel consumption could be partially offset by increases in travel or vehicle movements.

Some potential increases in VMT could be caused by a standard “takeback” effect. When the cost of travel declines, the amount of travel can be expected to increase. This is a straightforward effect of allowing a driver to multitask and increasing average speeds, both of which make the time cost of travel lower. As discussed earlier, this effect is likely to be small because of the low responsiveness of VMT to cost of driving and self-limiting because renewed congestion would eliminate the cost saving that causes a take-back effect.

A different reason for increased VMT unique to AVs could be movements of empty vehicles, such as personally owned vehicles returning home after a commute to be available for other family members or moving to a remote location for parking.
These effects on fuel consumption are side effects of the cost savings and convenience that AVs could provide to consumers and are not in themselves a barrier to AV deployment. Depending on how large these effects are, the benefits of AVs would be lessened from those estimated here, but the benefits would still remain. Takeback effects cannot wipe out the primary benefit, because the incentive to drive more is reduced when the induced additional driving brings back some congestion.

The introduction of driverless vehicles also creates possibilities of increased VMT by empty vehicles. For example, if a commuter uses the family AV to drive to work, then sends it home for use by the household during the rest of the work day, the VMT generated by the commuting activity would be doubled. Even if the AV is not sent home during the work day, the notion that AVs could take themselves off to remote parking locations after delivering their owner to work would increase VMT.

The same is possible if shared rides replace use of POVs. To the extent that shared vehicles circulate empty waiting to be summoned, their VMT will be greater than that involved in moving passengers. Shared vehicles could also spend up to 50 percent of their time cruising between assignments, unless scheduling and dispatch systems are greatly improved over current taxicab systems.

Increases in VMT for these reasons would to some extent be offset by increases in passengers per vehicle, especially in shared ride services. Even with conventional drive technologies, the expansion of shared ride services with AVs would lead to more passengers per vehicle, thus reducing the number of vehicle-miles required to satisfy existing travel demands.

Fuel savings in motor freight

As discussed earlier, self-driving trucks operating on interstate and other limited access highways could achieve in fuel consumption through platooning. These reductions in fuel use provide energy security benefits in addition to the private cost savings that accrue to freight companies and shippers. The reduction in fuel consumption per vehicle thought to be achievable by platooning is 10–15 percent with some estimates as high as 20 percent with very long convoys.[39]

In principle the reductions in freight cost due to platooning and reduction in labor costs could induce either modal shifts or increases in total freight volumes that would offset some fuel savings. No estimates of those potential take-back effects have been found.

Import premium

Three types of economic benefit of reduced oil consumption and imports have been identified. When expressed as dollars of benefit per barrel of oil saved these have been named an import premium, an energy security premium and an environmental premium. The import premium measures the savings on remaining oil imports due to the fall in imported oil prices attributable to a reduction in net imports (NI). The energy security premium represents the reduction in expected costs of oil supply disruptions attributable to lower levels of oil use and imports. The environmental premium is based on estimates of the avoided damages from air pollution attributable to lower oil consumption.

Lower gasoline consumption translates to a change in the global supply-demand balance that leads to a lower world oil price. The magnitude of the drop depends first of all on how much gasoline demand is reduced by the introduction of electric vehicles as shared AVs, and then on elasticities of world and U.S. oil supply and demand.

When the global market rebalances, the excess supply caused by the shift to EVs causes world oil prices to fall until the market is back in balance. The fall in oil prices causes world supply to shrink and global demand to grow, and it also leads to two offsets in the U.S: 1. some of the drop in global oil production would occur in the United States and 2. demand for gasoline and other petroleum products in uses not switched to electric vehicles would increase.

The World Oil Market Model developed by Baker and O'Brien takes all these effects into account.[40] I estimate that if the combination of use of EVs for shared services and reductions in congestion reduced oil use by 25 percent, or 2 million barrels per day (Mbd), under current market conditions the world oil price would drop by about $2.15 per barrel.

This drop in world oil prices benefits the U.S. in three ways. Remaining oil imports cost less because of the drop in price and this is a pure gain to the United States and loss to

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[39] Aviv Adler, David Miculescu, and Sertac Karaman "*Optimal Policies for Platooning and Ride Sharing in Autonomy-Enabled Transportation.*" Massachusetts Institute of Technology. https://www.extremetech.com/extreme/241442-mit-study-driverless-truck-platoons-will-save-fuel-money-especially-tailgate; http://wafr2016.berkeley.edu/papers/WAFR_2016_paper_110.pdf

[40] http://www.bakerobrien.com

other oil exporters. Lower prices allow some who could not previously afford to purchase gasoline or other refined products to do so, and this is also a net gain.

Results needed from the Baker-O'Brien World Oil Market Model include the reduction in the world oil price, which was estimated to be $2.15, and the resulting level of net imports, estimated to be 2.74 Mbd. In addition, the increase in domestic consumption of refined products induced by the lower world oil price was estimated to be 54,000 barrels per day.

The result is a net gain for the U.S. economy, purely from the fall in world oil prices triggered by the adoption of EVs in AV fleets that replace 25 percent of gasoline consumption. The resulting consumer surplus gain is about $2.15 billion per year.

Lower prices for gasoline in the United States lead to additional driving of the non-EV fleet of about 54,000 barrels per day, less than 3 percent of the saving from introduction of EVs. The net reduction in consumption after accounting for this take-back effect is used to calculate energy security and environmental benefits. The lower prices and demand also lead to reduction in US production of crude oil of about 496,000 barrels per day, which affects the size of oil security premium.

Energy Security Premium

A survey article[41] by Hillard Huntington and Stephen P.A. Brown provides estimates of the improvements in energy security caused by reductions in consumption of imported oil and domestic oil. They measure the premium as the change in expected GDP loss from oil supply disruptions caused by a one-barrel reduction in imports.

From their survey, Huntington and Brown report a range of $1.12 to $15.42 per barrel for the premium on imported oil consumption and $0.86 to $11.85 for domestic oil consumption. The reason for the higher premium on imported oil consumption is that it reduces the potential magnitude of oil supply disruptions by reducing production in insecure areas as well as vulnerability to those disruptions, while reductions in domestic oil consumption that are balanced by reductions in domestic supply result only in lower U.S. vulnerability to supply disruptions. They choose $5.31 and $4.06 as the most likely values for the two types of premium.

Modeling the oil import premium with the WOMM provided estimates of changes in domestic consumption and in imports that were used to calculate the energy security benefit of switching 25 percent of oil consumption to electric vehicles. Applying the Brown-Huntington premiums to the changes in imports and domestic oil consumption gives an additional saving of $3.5 billion per year.

[41] Brown, Stephen P.A. and Huntington, Hillard G. 2015. *Evaluating U.S. Oil Security and Import Reliance*. Energy Policy 79: 9-22 (April).

Environmental Premium

Several authors also discuss the environmental benefits of reduced consumption of transportation fuels. The most recent of these studies[42] estimates a benefit of $12.11 per barrel of reduced consumption. This translates into an additional saving of $15 billion per year

Total public benefit of reducing oil consumption

The total oil import, energy security and environmental benefit of replacing 25 percent of rides in conventional vehicles with rides in shared electric vehicles adds up to $20 billion per year.

Converting this central estimate to a range based on the SAFE scenarios of 12.5 percent and 75 percent EV penetration in shared fleets gives a range of benefits. Gasoline consumption would be reduced by about 1 Mbd if EVs used for shared ride services replace gasoline-powered vehicles for 12.5 percent of passenger miles travelled and 5.5 Mbd if they replace 67.5 percent. Platooning and lessened congestion could reduce fuel consumption by 270 to 405 thousand barrels per day. The total reduction in fuel consumption of 1.3 to 5.9 Mbd yields energy security and environmental benefits of $13 to $58 billion per year.

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[42] Parry, Ian, Heine, Dirk, Lis, Eliza and Li, Shanjun. 2014. *Getting Energy Prices Right: From Principle to Practice,* International Monetary Fund, Washington, DC.

V. System-Wide Effects of Increased AV Use

The lower travel cost provided by AVs would greatly increase job opportunities and ability to find the best and lowest priced goods and services.

The average shopping trip distance is 3.3 miles each way and average speeds are 30 miles per hour.[43] If the value of travel time for shopping and errands is set, as studies suggest, at 25 percent of the wage, that implies a value of lost travel time of 14 cents per mile. AAA estimates that operating cost including an adder for mileage-based depreciation equals about $0.40 per mile.[44] The sum of lost travel time and variable operating cost is then $.54 per mile.

If AVs reduce the time cost of driving by errands and shopping by 30 percent (see VOTT section), that would be a 4 cents-per-mile reduction in the variable cost of local trips including fuel, repairs, etc. That would lower the total cost to $.50 cents per mile, or a 7.5 percent reduction.

Reducing the variable cost of trips by 7.5 percent would make a shopping trip of 3.6 miles each way no more onerous or costly in an AV than the current average trip of 3.3 miles each way.

The geographic shopping region would expand from an area of 34 to 50 square miles providing 18 percent more opportunities to find better prices or quality.

The expansion of the job search region is much larger. The average commuting distance is 9.8 miles (4.9 one way) at an assumed speed of 15 mph, and the value of the driver's lost time for commuting is estimated at 50 percent of the wage. Just the improvement in the value of lost time from multitasking while the vehicle drives itself reduces that loss to 17.5 percent of the wage.

If AVs reached their full potential for eliminating congestion and increased speeds to the average uncongested speed of 30 mph, that would reduce travel time by 50 percent in addition to reducing VOTT per mile by 65 percent. The result is an increase in a tolerable commuting trip distance from 4.9 miles to 10 miles one way and a quadrupling of the job search area.

Increased geographic market size due to lower time cost

Retailers, and in particular big box stores like Costco, use travel cost models to determine the potential catchment area of new stores. Stores will only be located in areas with populations large enough to support the minimum size store. Larger stores can be

[43] Summary of Travel Trends 2009 National Household Travel Survey, p.23

[44] American Automobile Association *"Your Driving Costs 2017"* https://publicaffairsresources.aaa.biz/YDC/

operated more profitably, since the both employment and inventory per dollar of sales can be reduced. Population density and average travel speed determine the size of the catchment area for a new or existing store. If travel speed is increased or the time cost of travel is reduced, the catchment area for stores will be increased.

This increase in the size of the market served by an individual store is therefore an unambiguous benefit, but how it is shared between consumers and producers will depend on the structure of individual markets.

In the case of markets with population densities too small to support a minimum-size store, reduced travel cost could make those areas into viable locations. In the case of markets already served by some stores, lower travel cost will introduce greater competition among existing (and possibly new) stores leading to a greater share of the benefits going to consumers. In other cases, the larger market might bring more customers to existing stores but the improved economics might not be sufficient to induce additional entry or to include more alternatives in the geographic market. In these (probably rare) cases the bulk of the benefits would go to the merchant rather than the consumer. More customers would use the store, but additional competition would not drive prices down.

The basics of geographic price competition are illustrated with an example of two stores located on a highway. Each store will increase prices to the point that the revenue gained on its retained sales equals the revenue lost from customers who switch stores. The customers that switch will be located between the stores. Thus, the lower are transportation costs, the more readily customers will switch from one store to the other in the event the first raises its prices. Therefore, for any price chosen by store A, the optimal price for store B to charge declines as travel cost declines. The same is true for store A for any price chosen by store B. Since both "offer curves" are shifted downward, there will be lower equilibrium prices as well in both stores.

The size of the geographic market has been critical to several cases in which the FTC required merging grocery chains to divest stores that they judge to be within a common geographic market, so as to maintain competition for consumers in that market. Their criterion was that the more stores a consumer had access to, the lower would be the prices those stores would offer.

In one such case, the FTC observed that "Consumers generally do not travel more than two to three miles to do their grocery shopping."[45] In another, it opined that "The

[45] FTC v. The Kroger Co., Plaintiff's PI Brief, June 2, 2000, p.10 https://www.ftc.gov/sites/default/files/documents/cases/2000/06/krogerbrief.pdf.

relevant geographic market in which to assess the competitive effects of the acquisition is a roughly three to three-and-a half mile area surrounding Newtown[.]"[46]

Indeed, the FTC itself recognized that the size of the geographic market depends on the convenience of travel:

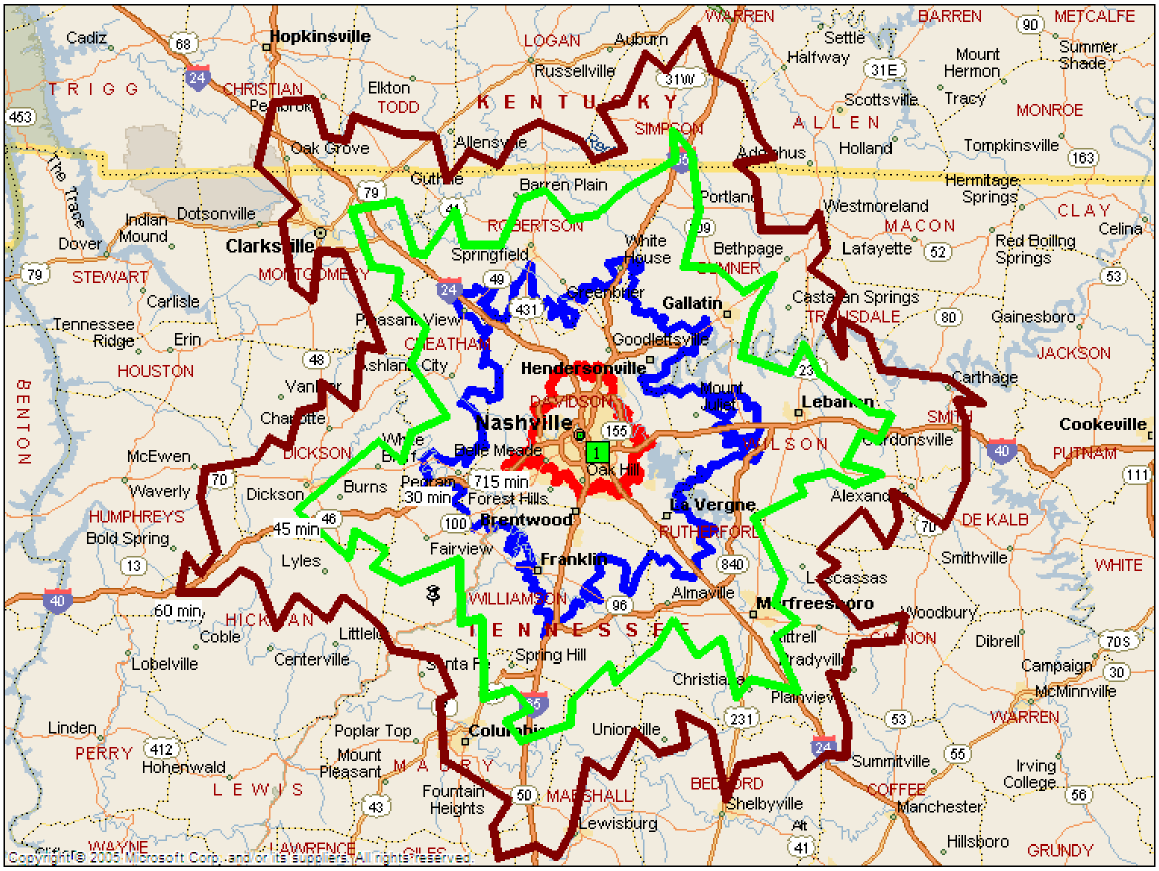
> "Convenience motivates supermarket customers' choices; consequently, consumers predominantly shop very close to home. However, the distance a consumer is willing to travel for groceries varies by local conditions and store type. For example, grocery consumers are often more willing to travel farther in rural or suburban areas than in dense urban areas. Moreover, geographic features of an area, such as valleys, parks, waterways, highways, railroad tracks, and bridges (or the lack thereof) can affect a customer's willingness to travel. "[47]

What all these observations and opinions point out is that convenience of travel is a key determinant of where people shop. Introduction of AVs would change rules of thumb for the size of relevant geographic markets by lowering the cost of searching further from home for the best price.

[46] Complaint ¶ 16, In the Matter of Koninklijke Ahold N.V., Docket No. C-4367 (Aug. 16, 2012) https://www.ftc.gov/sites/default/files/documents/cases/2012/08/120817konkinlijkecmpt.pdf.
[47] OECD, *"Competition in the retail grocery sector in Latin America and the Caribbean"* https://www.ftc.gov/system/files/attachments/us-submissions-oecd-other-international-competition-fora/structural_issues_in_the_groceries_sector-lacf_2015.pdf

The map below shows the approximate drive time zones based on leaving downtown Nashville and the lines represent the distance covered for 15 mins, 30 mins, 45 mins and 60 minutes.

FIGURE V-1: Drive times around Nashville TN

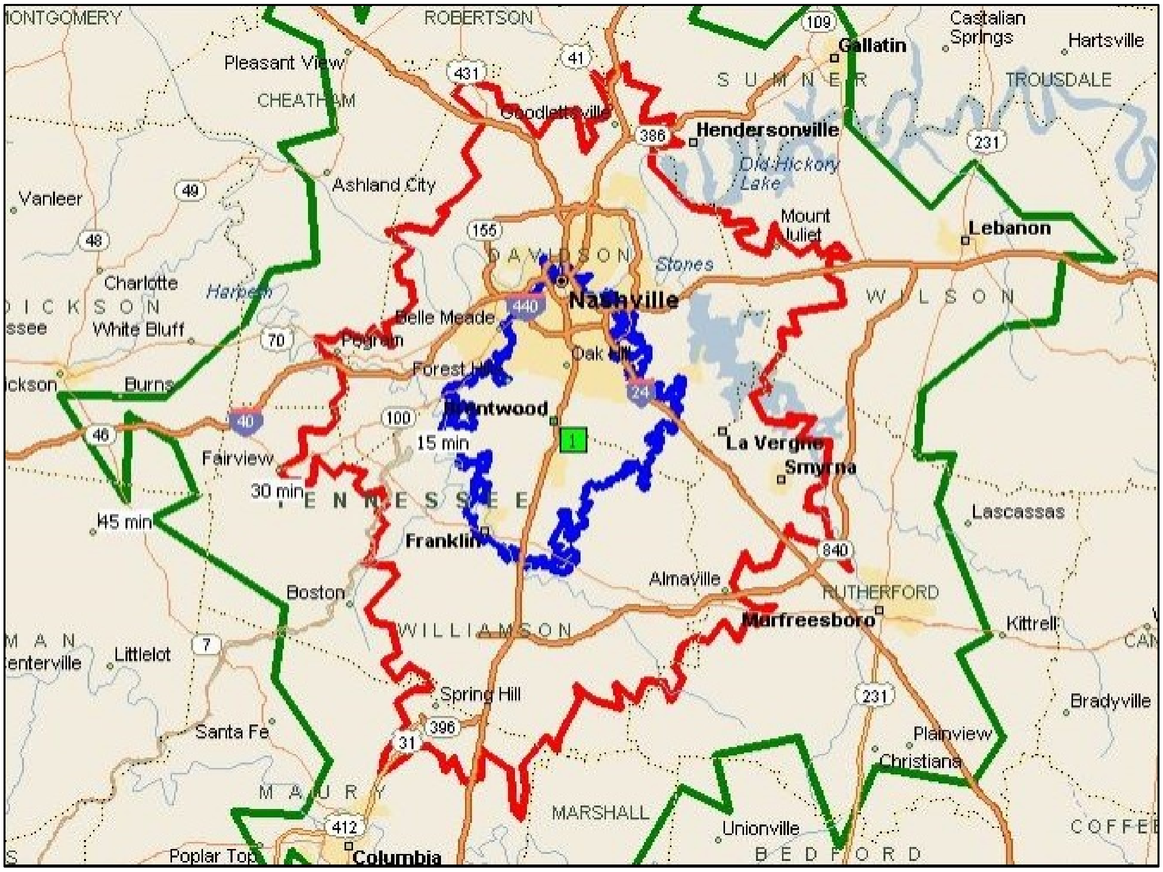


Red = 15 minutes Blue = 30 minutes Green = 45 minutes Brown = 60 minutes
Source: http://www.nashvillesmls.com/images/12955962.gif

If average speeds are increased, then a shopper living downtown can go a longer distance in the same amount of time. If time is used more efficiently, then the driver can travel further with the same time cost or inconvenience.

Average drive times leaving the suburban town of Brentwood are shown in the map below. For example, if AVs reduce the cost of travel time by 50 percent, a worker who was not willing to drive more than 30 minutes would find her job search area expanded from the red boundary to the green boundary, picking up the towns of Lebanon and Columbia and the city of Murfreesboro.

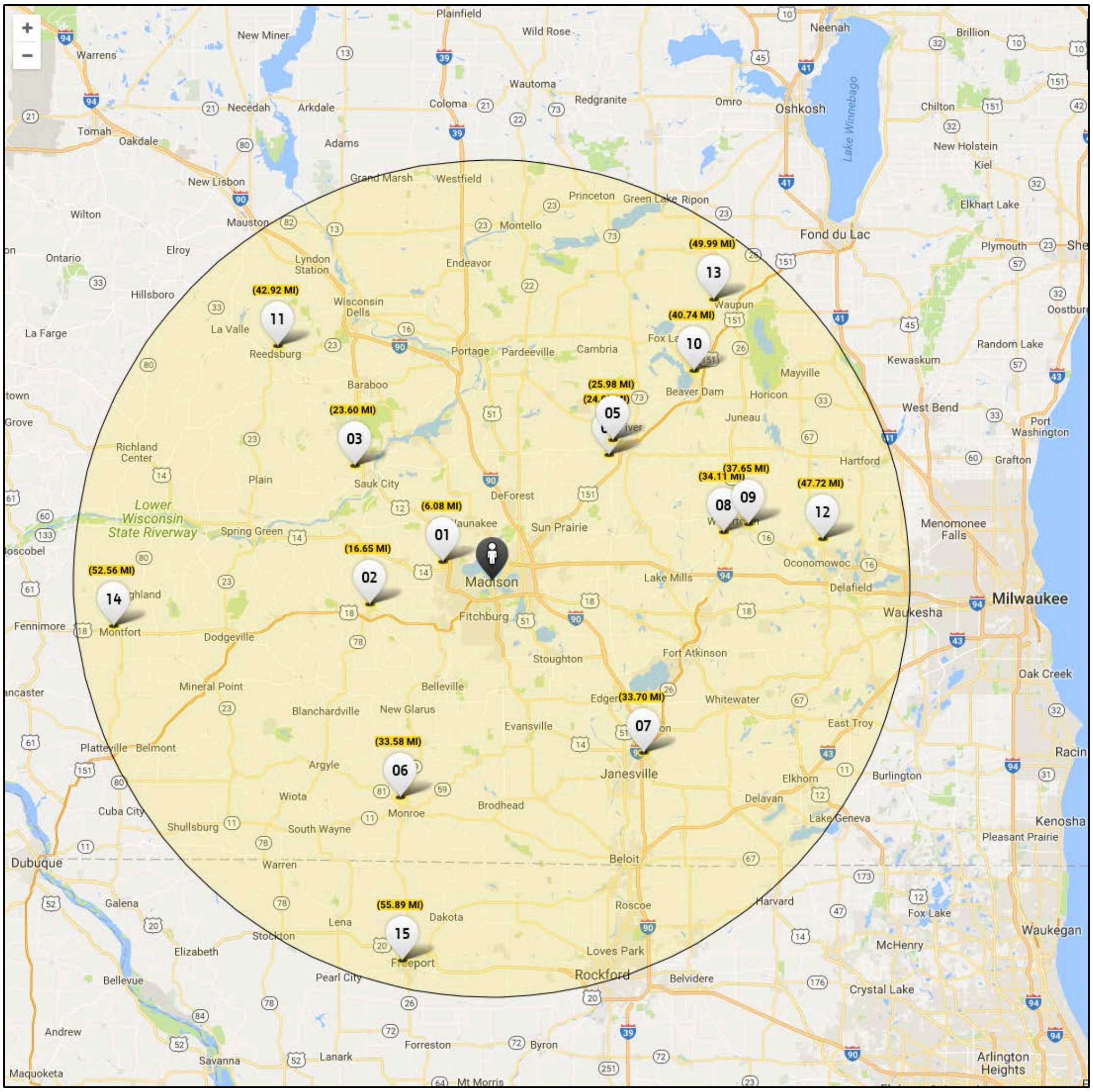
FIGURE V-2: Drive times around Brentwood TN



Blue = 15 minutes Red = 30 minutes Green = 45 minutes
Source: http://www.nashvillesmls.com/brentwood-tn-drive-time-map.php

For another example, if someone in Madison, WI wanted to search for the best deal on a John Deere lawn tractor and was willing to drive only 20 miles with current drive times, they would be able to visit just two dealers. If AV made the time cost of a 30-mile drive the same as that of a 20-mile drive with a driver-operated vehicle, the number of dealers would expand to five, and if a 35-mile drive became equivalent the number would expand to eight, with a ninth very close to the eighth.

FIGURE V-3: John Deere dealers around Madison, WI



Source: https://dealerlocator.deere.com/servlet/country=US?locale=en_US

The larger search radius for jobs has several broad economic consequences. It benefits both employer and worker by allowing better matching of job candidates to available positions, by giving employers a larger pool of workers to choose from and workers a larger number of potential offers to evaluate.

The result of improved job matching is higher productivity, leading to higher wages. This in turn leads to greater labor market participation and increased employment numbers overall, as those who dropped out of the labor market because of lack of success finding a job or who chose homemaking over paid employment find the balance tips in favor of going out and searching for a job.

Improved shopping opportunities imply that product and price search costs less, so that it is possible to find better bargains or higher quality goods and shopping experiences. From the retailer’s point of view, the expanded ability of customers to shop around means greater competition in price and quality, all of which benefits the consumer.

Some benefits to the worker and shopper of lower search costs and improved access may be internalized and included in stated WTP, to the extent that they are driven by the time saving that arises from multi-tasking while traveling. However, the increased radius attributable to higher average speeds due to congestion reduction are purely public benefits due to the congestion reduction externality.

VI. How Benefits Grow Over Time

Discussion so far is for a steady state in which a vehicle population and VMT like today's is fully converted to AVs. The penetration of AVs will grow over time and is limited by the turnover of the fleet as new vehicles replace retiring ones. The two penetration scenarios provided by SAFE provide two sets of assumptions about how this turnover process will work out.

Beyond rates of penetration of AVs in the fleet, there is the question of how the benefits described for a fleet fully converted to AVs are related dynamically to the penetration of AVs into the fleet. Some may be linear in penetration, while others may increase little or at all until and inflection point is reached at some higher level of penetration, after which benefits could rapidly approach the steady-state value for a fully converted fleet.

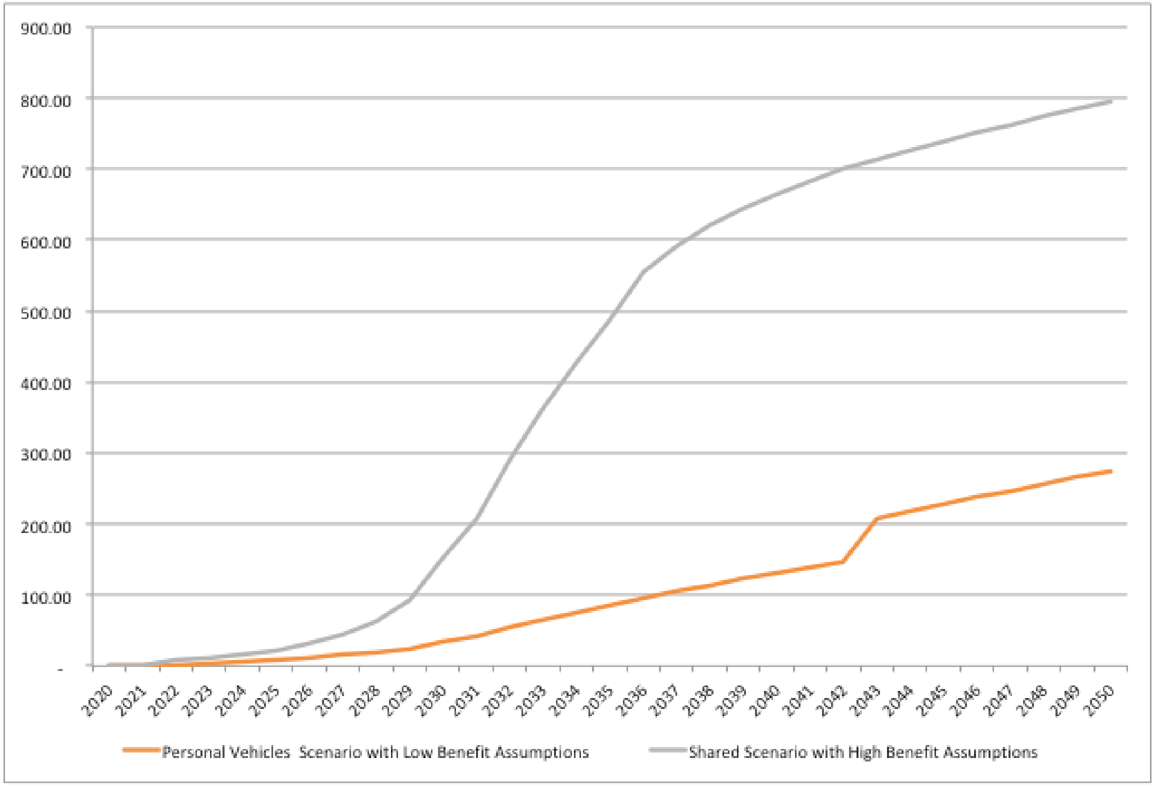
To give a rough estimate of the rate of growth of benefits, benefit estimates are divided into three groups with different dynamics. The implications of this division are different for two SAFE penetration scenarios, as shown in Table VI-1.

TABLE VI-1: Dynamic Penetration Assumptions

Category	Low path	High path
Oil consumption benefits	Grows proportional to shared vehicles	Grows proportional to shared vehicles
Congestion benefits	None before 75 percent total penetration Grows proportional to total penetration from 75 percent up to 100 percent	None before 10 percent Proportional from 10 percent to reach 100 percent of benefit at 66 percent penetration
All the rest	Grows proportional to total penetration	Grows proportional to total penetration

Figure VI-1 shows the growth in benefits for each of the scenarios developed by SAFE combined with the low and high end of the ranges of benefits estimated to be possible with all vehicles on the road converted to AV. The orange line combines the SAFE scenario dominated by passenger vehicles and slower penetration with the low end of the benefits range, and the gray line combines the faster SAFE scenario with the high end of the benefits range.

FIGURE VI-1: Increase in Benefits Over Time with AV Penetration
(Billion dollars per year in constant 2017 dollars)



VII. Adding It All Up

Summary of benefits of each type in isolation

All benefits were initially estimated assuming that AVs are 100 percent of the on-road fleet of vehicles.

Private benefits that motivate buyers:

- Three different ways of computing these benefits were evaluated.
  - Surveys of new car buyers who are now willing to purchase AVs reveal they would gain a benefit worth over $99 billion per year from the ability to purchase fully autonomous vehicles.
  - Bottom up calculations of private benefits from more efficient use of time while in the vehicle suggest even larger benefits, of $182 to $219 billion annually.
  - Reduced taxi/Uber labor cost giving benefits of $3.9 to $10.6 billion

- Reduced freight labor cost of $90 billion, if only platoons of long distance trucks are AVs (based on cost data assuming 10 percent margin and five truck platoons) up to $296 billion if all drivers were replaced with CAV.

- Reduced freight fuel cost of $1.6 to $2.4 billion per year.

- Range for private benefits including passenger and freight is $195 billion to $528 billion per year.

- The benefits of more intensive use of vehicles by family members and need for fewer vehicles for family transportation would be additional.

The public benefits of AVs that justify policies to accelerate their introduction include:

- Congestion reduction with a potential value of $71 billion per year from savings in time and fuel for POV (including capacity, timing and accident cause elimination)

- Benefits of reduced accidents of $118 to $500 billion per year.

- Reduced gasoline consumption of about 1 Mbd if EVs used for shared ride services replace gasoline-powered vehicles for 12.5 percent of passenger miles travelled and 5.5 Mbd if they replace 67 percent.

- Reduced diesel consumption of 100,000 to 170,000 barrels per day if convoys lead to a 10–15 percent reduction in fuel use by tractor-trailer combinations. This is a cost saving of $2.7 to $4 billion using late 2017 prices of $1.75 per gallon before tax. (Before tax is used because fuel taxes fund highway expenditures and are likely to be raised as demand falls, so that the private and social saving from reduced consumption is just the ex-refiner cost.)

- Oil consumption related benefits of $13 to $58 billion per year due to fuel savings from electrification of fleet AVs. These include lower prices for imported oil, reduced risks of oil price spikes and supply disruptions, and environmental benefits from lower motor vehicle emissions.

Possible overlaps

These categories of benefits are defined to be separate from each other to eliminate double counting as far as possible.

There is an interaction between willingness to pay, however estimated, and reductions in congestion. Since relieving the driver of responsibility for the vehicle while traffic is congested has a higher value than doing so when there is no congestion, willingness to pay for AVs would be expected to decline as congestion is reduced. Therefore, when adding up benefits, WTP should be adjusted downward by removing the benefits of AVs during congested conditions and increasing benefits of AVs in non-congested conditions. This amounts to a reduction of 30 percent in the estimate of $98.5 to 219 billion as willingness to pay based on value of travel time, reducing it to $69 to $153 billion.

It is also possible that some of the private benefits of accident reduction are double-counted. That is, if buyers of AVs include in their calculus the expectation that they will avoid single-car accidents, then the same fraction of the avoided cost of single-car accidents should be subtracted from the $350 billion annual value of accident reduction.

There is a linkage between accident reduction and congestion reduction because a substantial fraction of wasted time is due to congestion caused by accidents. However, there is no double counting here because the cost of accidents has already been adjusted to move time savings into the congestion related category.

The combined figure

Taking all these adjustments into account, the total annual benefit of AVs with 100 percent penetration of the fleet of passenger vehicles would be $275 billion to $796 billion per year.

In order to display the full range of uncertainty about benefits, the more aggressive penetration assumptions of the shared scenario were combined with the high-end estimate of benefits with 100 percent penetration. Similarly, the less aggressive penetration assumptions of the scenario in which personal vehicles dominate were combined with the low-end estimate of benefits with 100 percent penetration.

Benefits in the two scenarios, taking into account overlaps among benefit categories, are summarized in Table VII-1:

TABLE VII-1 Summary of Benefits (Annual $Billion with 100 percent AV Penetration)

Category	High	Low
Public Benefits At 100% of VMT (annual)	**633**	**202**
Congestion	71	71
Accidents -- Repair and Medical Expense	118	118
Accidents – Pain and Suffering	385	-
Reduced Oil Consumption	58	13
Private Benefits at 100% of VMT (annual)	**163**	**73**
Value of time	153	69
Reduction in Cost of Taxi/Uber/Lyft Service	10	4
Total Annual Benefits in Personal Transportation	**796**	**275**
Freight Cost Reduction	**298**	**92**

Figure VI-1 showed how the benefits for passenger transportation would grow over time. Under the lower of the two scenarios developed by SAFE, the slower penetration rate with personal vehicles dominating leads to an almost linear growth in benefits. Benefits in this scenario would reach the lower benefit level of $275 billion in the year 2050. The small kink in Figure VI-1 occurs in the year when penetration of AVs reaches the threshold assumed for congestion reduction.

SAFE's aggressive scenario with more rapid introduction of AVs in shared vehicle applications assumes that sales of AVs will begin sooner and increase more rapidly, and that congestion benefits start at 10 percent penetration. Half the ultimate benefits in this scenario would be achieved by 2035, compared to achieving half the ultimate benefits in 2043 in the slower personal vehicle scenario. When AVs replace all conventional vehicles on the road, benefits in the high case would be $796 billion.

Benefits from AVs in the trucking industry would be additional to these passenger car benefits, and could be from $92 to $298 billion, depending on how completely drivers are eliminated.

Taking the present value of the personal vehicle savings (at a social discount rate of 3 percent) gives estimates of the value of moving the entire personal vehicle fleet to Level 4 or 5 automation according to the SAFE scenarios.

The present value of that benefit at the standard 3 percent (real) rate for discounting government investments could be from $3.2 to $6.3 trillion over the 32-year period from 2018 to 2050.

For comparison, one study[48] estimates the value created by the Interstate Highway System over the longer 40-year period from 1956 to 1996 as about $1 trillion in 1996 dollars or $1.5 trillion in today's dollars.

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[48] Wendell Cox & Jean Love, *The Best Investment a National Ever Made: A Tribute to The Dwight D. Eisenhower System of Interstate and Defense Highways*, American Highway Users Alliance, June 1996 http://www.publicpurpose.com/freewaypdf.pdf

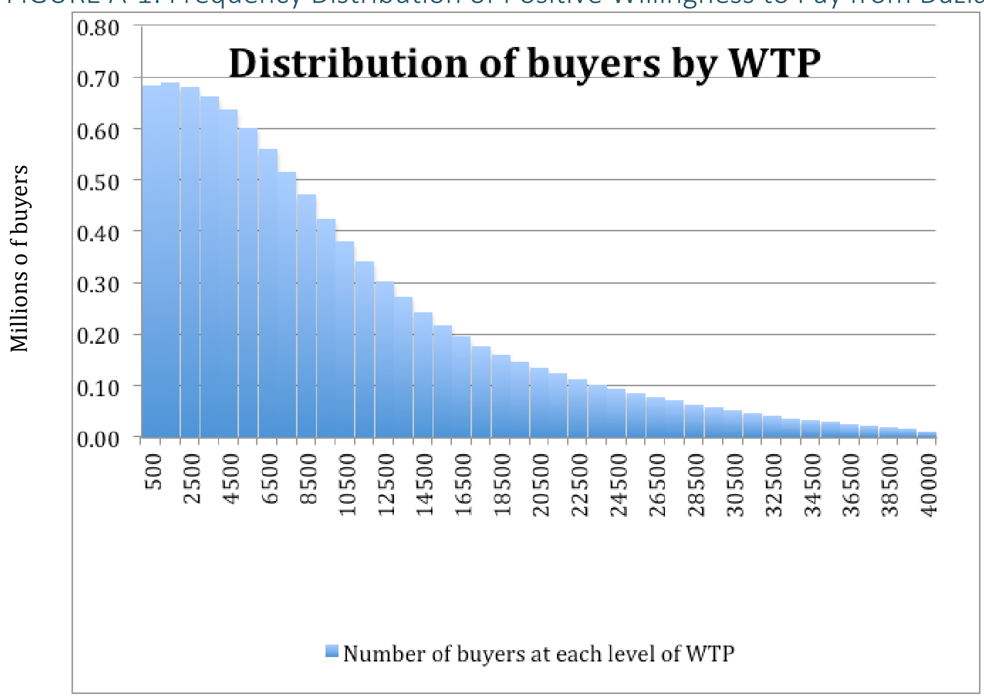
Appendix A: Estimation of Private Benefits

A.1 Consumer Surplus Based on WTP Survey

I use the survey results from Daziano et al. that they designate as most representative and reliable. Daziano et al. divided the sample into three groups, based on respondents' knowledge of AVs as elicited with questions on the survey. The paper reports the sample size and the mean and standard deviation of the responses for each of the three groups. From these statistics and data on new vehicle sales it was possible to convert the sample percentages into numbers of new vehicle purchasers.

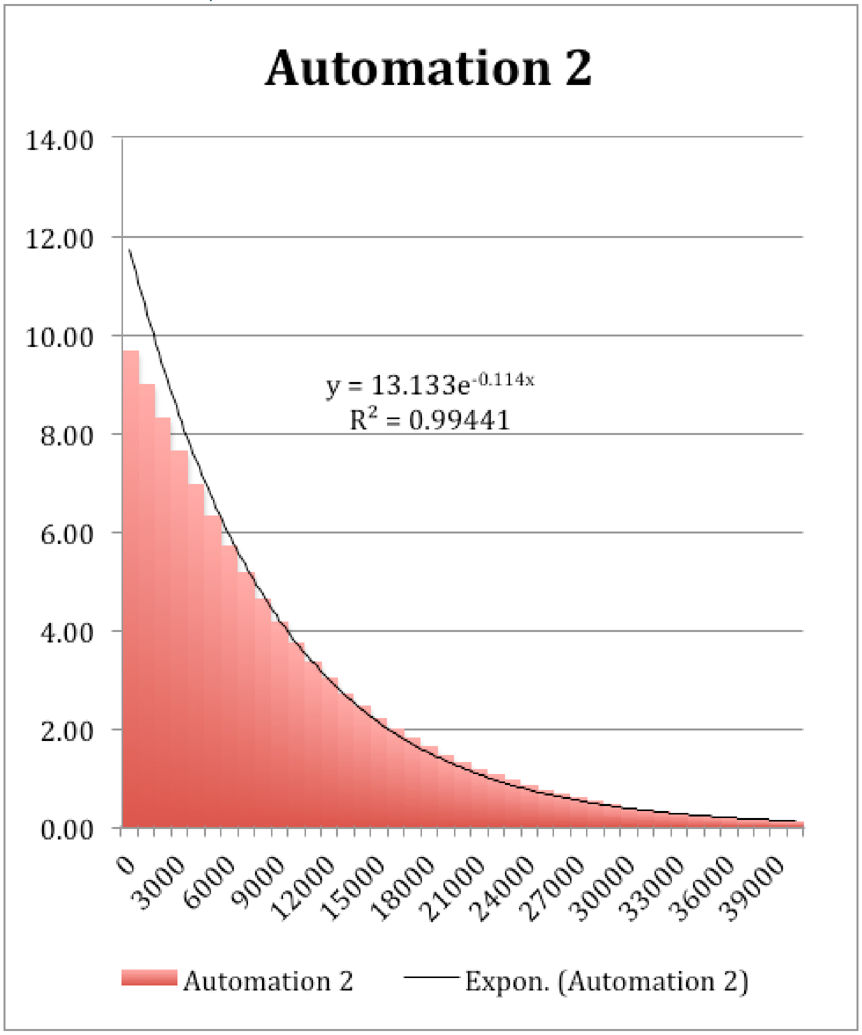
In Figure A-1 the percentage of respondents is plotted against willingness to pay for full automation in $1000 increments. Daziano et al. refer to Levels 4 and 5 as "Full Automation."

FIGURE A-1: Frequency Distribution of Positive Willingness to Pay from Daziano et al.



These sample percentages can be applied to actual new car and light truck sales to calculate the number of vehicles that would be sold at each increasing step in price. This is the classic demand curve and is plotted in Figure A-2.

FIGURE A-2: Empirical demand curve based on Daziano et al.



The height of each column represents the number of new car and light truck purchasers willing to pay no more than the amount specified at the bottom of that column to have a Level 5 rather than Level 2 AV. Thus there are 9.7 million purchasers of new vehicles (out of a total of 17.5 million per year) willing to pay more than zero as the incremental cost of an AV. At the other end of the scale, there would be just 10,000 willing to pay up to $40,000 in incremental cost for an AV.

To compute aggregate consumer surplus we switch the axes and plot the amount each group of buyers is willing to pay against the number of new cars purchased by that group. Thus there are 9,000 buyers willing to pay up to $40,000 and 410,000 willing to pay up to $30,000 extra. At the other extreme, there are 9.69 million buyers willing to pay something, 9 million of which are willing to pay more than $1000 extra.