Connected Autonomous Vehicles: Travel Behavior and Energy Use

Jonathan Rubin

Abstract Autonomous vehicles offer great promise for unprecedented improvements in mobility and safety. However, self-driving vehicles may also significantly alter behavior because they can make driving easier and safer. This may lead connected autonomous vehicles to have large unintended consequences in terms of additional energy use and greenhouse gas emissions, as well as causing decreases in the density of urban areas and may impact congestion. This paper uses consensus estimates from the literature on the cost of driving and the value of travel time to evaluate automation's ability to reduce the costs of travel time. Policy solutions to address the induced driving include charging for miles driven taking into account when and where vehicles are used.

Keywords Autonomous vehicles · Energy use · Travel costs · Economics

1 Introduction

Automated vehicles offer great promise for unprecedented improvements in mobility and safety. In anticipation of this technology, a growing number of US states have enacted legislation that permits operation of self-driving vehicles under restricted conditions designed to determine their use and compatibility on public highways [1] These experimental vehicles are at the higher end of a wide range of automation that begins with some safety features already in vehicles, such as electronic stability control and antilock braking systems. The US National Highway Traffic Safety Administration [2] defines vehicle automation as having five levels from no automation (Level 0) where the driver is in complete and sole control of the primary vehicle controls, to full self driving automation (Level 4). The Society of Automotive Engineers has a similar, classification system but splits Level 4 into two categories,

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one mode-specific (e.g., highway) and one that can operate in all modes and weather conditions [3]. Currently, automated features including adaptive cruise control and lane keeping are being introduced on premium model lines of various manufacturers. These are generally considered Level 2 automation since they involve "automation of at least two primary control functions designed to work in unison" but still require drivers to monitor and be responsible for the vehicle at all times.

The higher levels of automation, Level 3 and above have the vehicle performing all aspects of driving such that drivers are able, under a variety of circumstances depending on level of automation, to perform other tasks. This aspect of automation is likely to significantly alter driver behavior because it allows for a more enjoyable driving experience where the driver can engage in other activities. Additionally, high levels of automation may enable higher speeds that cause road travel to be more competitive with aviation (for passengers) and rail (for freight).

The higher levels of automation require automated vehicles to be connected to real-time route mapping software and allow for optimizing road situational awareness such as anticipating congestion and construction obstacles. While connectivity enhances or is required for AVs, connectivity is also increasingly becoming integrated with new vehicles that will not have higher levels of automation. Thus, from a behavioral perspective, connected highly automated vehicles (CAVs) differ from connected vehicles (automation Levels 1 or 2) in their ability to allow drivers to perform other tasks, but do not necessarily have advantages in terms of optimal route finding.

Due to the behavioral responses of drivers, CAVs may have large unintended consequences in terms of additional energy use and GHG emissions in the transportation sector and may also have the potential to further decrease the density of urban areas. This paper uses consensus estimates from the literature on the cost of driving and the value of travel time to estimate the potential increases in driving due to automation. Policy solutions to address the induced driving are discussed. The barriers to meaningfully reduce the impact of driving are also acknowledged.

2 Literature Review

There is a small literature that tries to look at the likely impacts of CAVs on driving and energy use [4–8]. As a whole they tend to be optimistic about the benefits of the CAV technology. Mackenzie et al. bound the long-term (2050) energy implications of road vehicle automation using a Kaya Identity (ASIF) based on the framework of Shipper [9] where emissions and energy are given by:

$$Emissions = \boldsymbol{A}ctivity\,Level \cdot Modal\,\boldsymbol{S}hare \cdot Energy\,\boldsymbol{I}ntensity \cdot \boldsymbol{F}uel\,Carbon\,Content$$

They identify a number of ways in which Level 4 automation may have a significant impact on many important aspects of personal vehicle use. These potential impacts include (in part): reductions in congestions, improved crash avoidance, higher highway speeds, vehicle platooning, traffic smoothing (efficient driving), improved routing, reduction in the time and insurance costs of ownership and the enabling of new user groups such as the elderly and the disabled. As noted, CAVs can also potentially increase energy and emissions by inducing additional and faster driving, and by drawing in underserved populations (disabled and elderly drivers).[1] Because of the inherent uncertainties, Mackenzie et al.'s estimated range of impacts on transportation travel demand, energy use and GHG emissions, is very large, −40 to +100 %. This range becomes smaller if only considering changes due to automation, not vehicles, vehicle costs or improved routing from increases in connectivity.

Fagnant and Kockelman [8] note that shared autonomous vehicles (SAV) may increase the use of car sharing programs such as Car2Go and Zipcar by reducing the barriers, including users' need to travel to access available vehicles. Their simulation results show that, in an urban setting, each SAV can replace around eleven conventional vehicles, but adds up to 10 % more travel distance than comparable non-SAV trips, resulting in overall beneficial emissions impacts. It is unclear, however, how much of this savings is due to lower per vehicle emissions of the SAVs, which are all sedans, as compared to the US average light-duty vehicle fleet that includes light-duty trucks and SUVs.

What is important to understand from a perspective of the realized impacts of CAVs are the factors that influence how they will be used and by whom. While potential vehicle efficiency improvements and other system optimizations matter, the largest impacts are likely to come from how consumers react to automation in terms of use: how often, when and how much they use their vehicles. This is largely determined by the full cost and value to drivers who decide to take a trip by car, use public transportation or walk. CAVs will only enter the market place and be privately purchased because they enhance driving. Clearly, enhanced safety and access to mobility by users limited by age or ability is an unmitigated benefit. Beyond this, increasing amounts of automation will only be purchased because they will provide drivers with an improved quality of travel time, allow for drivers to participate in non-driving activities and may enhance drivers' perceived sense of social status.

3 Costs of Driving

The total cost of operating a vehicle varies depending on the type of vehicle, when and where the vehicle is used and for what purpose (work or leisure). The marginal cost for an additional mile includes fuel, tire wear, tolls and the time and pleasure or displeasure of the driver while driving. The average cost for some length of period

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[1] A number of these papers also identified other potential impacts such as changes in vehicle performance and weight and the possibility of increased use of alternative fuel vehicles.

includes oil and maintenance, and can also include fixed costs such as insurance, registration fees, financing and the vehicle purchase price. This distinction between marginal and incremental costs is especially important with the growth of services such as Zipcar, Uber and Lyft that offer mobility without the need for vehicle ownership. These services must recover the full average costs of driving per trip and, hence charge larger marginal costs per miles than privately owned vehicles including CAVs.

The Rand Corporation uses data from AAA to estimate that household could save about $5,700 in fixed annual costs by joining a car-sharing program rather than owning a vehicle [10]. They note that these same underlying costs passed back to members in the form of higher per mile rates apportioned over 10,000 miles would be about 57 cents per mile. Added together with the 21-cents-per-mile cost for fuel, maintenance, and tires, the per-mile cost of a car-sharing plan would then be about 77 cents per mile. This compares to about $11–14/h for a Zipcar car in the greater Boston.

Small and Verhoef [11] tally the costs of a typical urban commuting trip in the United States, finding that travel time and reliability—travel time costs (TTC)—together account for 45 % of the average social variable cost, compared to vehicle capital costs (19 %), vehicle operating costs (16 %), and accident costs (16 %).

As seen in Fig. 1, from an individual's cost perspective the total cost per mile $1.02 for new sedan is divided into ownership costs of $0.41/mile (average annual depreciation, license and registration fees, cost of insurance and finance charges)

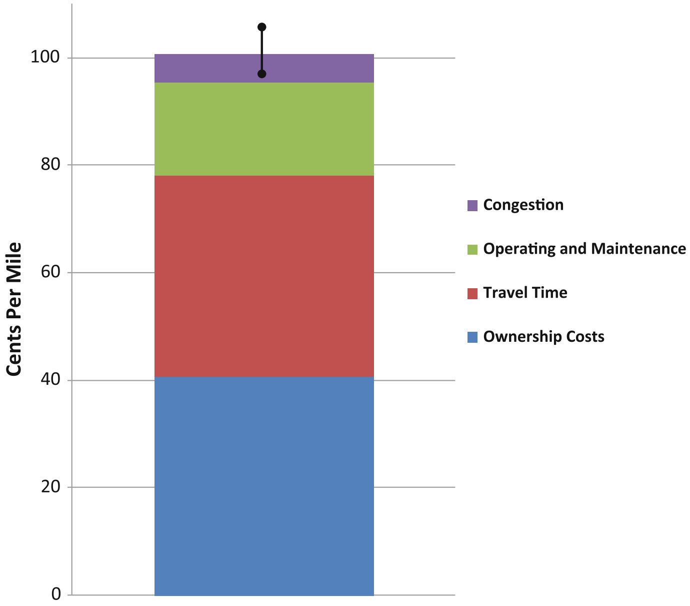

Fig. 1 Average individual cost of travel per mile (cents/mile), range on congestion (*sources* [12, 13] and author's calculations)

[12] divided by the annual miles [14]. The travel time costs of $0.37 is the average time spent driving in free flow traffic divided by the average distance driven daily in the US [15] and multiplied by the average US TTC per hour ($18) [13].

Operations cost of $0.17/mile is the cost of tires, gas and maintenance per mile [12]. Congestion is the average annual individual cost of congestion including time premiums, time delays and additional fuel expenditure per mile [13]. Congestion costs are highly variable from 0 (no congestion) to a small urban area (population less than 500,000) the average congestion costs are 5 cents per mile to a major metropolitan area of 11 cents per mile.

The TTC is one of the largest components of costs borne by individuals. The range of TTCs is large reflecting the wide variation in travel purpose such as commuting to work, while working, or for leisure or shopping. The range in TTC also reflects differing values of time due to socio-economic circumstances such as wealth and age.

Travel demand is usually thought of as derived demand from scheduling many activities including work, recreation, shopping and so forth. This view goes back to the time budgets framework postulated by Becker [16] where individuals and households maximize utility by dividing activities between leisure, wage income and travel time.

3.1 Value of Travel Time

The value of travel time is the implicit monetary value (cost) that individuals place on their time while traveling.[2] The US Department of Transportation (USDOT) summarizes the literature by noting three underlying principles [17]: time spent travelling could be spent productively (e.g., working), recreationally (possibly spending money) and time spent travelling may be unpleasant and cause fatigue, hurting productivity. CAVs are likely to impact all three factors. Drivers could make telephone calls, work on a tablet, or browse the internet, as the vehicle is responsible for route finding and other driving operations. This means that highly automated CAVs will cause a significant decline in TTC. The other advantage CAVs have over, say a train, is that they are a private, door-to-door service. The best comparison might be a private vehicle with a hired driver.

The value of time that affects travel decisions likely depends strongly on factors that vary significantly by individual and are difficult to observe. These factors include individual tax rates, ability to use travel time productively, fatigue or displeasure from travel, ability to adjust working hours and times, and the importance of being on schedule for work or appointments [11, 17–22].

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[2] The literature variously refers to costs of travel as travel costs, value of travel time and other variations on the opportunity cost of time spent traveling from one activity or place to another. This paper uses TTC for this common concept.

The papers by Small [19] and Small and Verhoef [11] provide a comprehensive review of the travel time literature. They point out that drivers care not only about the amount and value of time per trip, but also the value of reliability, that is how likely is it that a trip of uncertain travel time can be completed within some expected time costs of congestion.

Shires and De Jong [21] conducted a meta-analysis of TTC accounting for the type of data set (stated and revealed preference), type of transportation, wealth of the country (GDP per capita), the age of the data set, region of country (Northern Europe, Southern Europe, Other), length of distance travelled and the variance. They discovered (largely cross-sectional) income elasticity of the TTC of about 0.5 for business travel, 0.7 for commuting and 0.5 for other passenger transport. Long distances lead to higher TTC for commuting and other purposes.

Abrantes and Wardman [21] performed a meta-study on TTC values drawing on 1749 valuations and 229 British studies from the following modes: in vehicle time, free flow time, congested time, walk time, access time, wait time, headway, departure time shift, and late time. They found a GDP elasticity of 0.9, a distance elasticity of 0.16, and that congestion raised TTC by 34 %. Business travelers were found to have a TTC nearly twice that of non-business travelers and commuters to have a TTC 10 % higher than other non-business travelers.

Driving in congested traffic drives up the TTC of travelers in comparison to free-flowing traffic [11, 19, 21, 23]. Steimetz [23] research uses revealed preference data where drivers have the option of purchasing access to a less congested toll road. He finds that driving in congested conditions is valued more negatively than non-congested driving and that a decomposition that shows about 40 % of TTC in congested time periods is risk and accident avoidance effort. This is significant for CAVs (Levels 3 and 4) since one of their major benefits is automated accident avoidance traffic smoothing.

As noted earlier, there is also the related issue of reliability of travel time [24]. Travelers are willing to pay more for less variation in their travel time. This concept is called value travel time reliability (TTR), and plays a significant role in an agent's decision making process especially for those with a fixed work schedule with a penalty for being late. Carrion and Levinson [24] find that like TTC, TTR varies across regions, time of day and length of journey. Connected vehicles, automated or not, should increase the ability to predict travel times, improve routing and reduce travel time reliability costs for individuals. Small [19] notes that improved information provision may also change the spatial and temporal pattern of congestion.

3.2 CAVs and Rebound Driving

As Small [19] notes, it is widely believed that better in-vehicle amenities, mobile communications, and entertainment devices lower the value of time by making travel time less onerous or more productive. However, as he notes, telecommunications appears to be complementary to rather than a substitute for transportation as individuals and businesses have transformed the way people interact. CAVs are like amenities, but at a whole different level since at Level 3 and above, they can provide work and leisure opportunities while driving. This calls into question the classic time budget framework used in transportation demand modeling.

In the standard analysis of rebound driving, induced travel comes from energy savings from increased vehicle efficiency which lowers the cost-per-distance of travel. These lower costs of travel are then passed on to reduce costs for other industries which lead to reduction in prices and increases in profits [25]. With CAVs, however, decreases in travel costs arise from savings in TTC. For non-business travel, this ought to have the same impact as a reduction in fuel costs per mile to encourage additional driving. For business travel, it is not as clear what the impact might be unless the driver is able to do productive work while traveling in which case per mile costs of travel are also lower. Nonetheless the direction of the effect is clear. CAVs will cause more driving to occur and could cause additional low density development as households and firms adjust to lower transportation costs.

From a welfare theoretic perspective Chan and Gillingham [26] note that there is an important difference between efficiency gains that cause externalities that arise from rebound effects on energy use and those that arise from energy service consumption such as congestion. Energy service rebound effects will increase with increased energy efficiency and lower welfare where as rebound energy with efficiency gains may or may not grow depending on the magnitude of rebound effects. However, lower TTC do not in and of themselves lower the energy use per distance and hence the rebound impact will lower welfare from marginal congestion and increase energy use. The other, indirect (substitution) rebound effects that may occur are from additional driving due to substitution away from public transport as the relative cost of CAVs falls.

4 External Costs of Driving and CAVs

Shown in Fig. 2 are the cost per mile to society from driving, about 18 cents. The cost of accidents at 8 cents per mile is the annual expenditure on automobile accidents in the US divided by the total vehicle miles traveled [1]. The cost of congestion is the absolute wages lost to society by delays caused in congestion for a small urban city [27]. The cost of carbon dioxide of 2 cents per mile is the average tonnage of CO_2 emitted by a car per mile [28] times the cost to society of a ton of carbon dioxide [29]. Criteria pollutants cost of 2 cents per mile [30]. Finally, the cost of fuel insecurity of 1 cent per mile is the estimated macroeconomic disruption component in dollars per gallon of the US dependency on imports [31].

A question arises: are the external costs of driving, on a per-mile basis, significantly influenced by automation? If there are no changes to when and where vehicles are used then this is likely correct. On the other hand, if automation increases the prevalence and use of CAVs relative to connected or non-connected

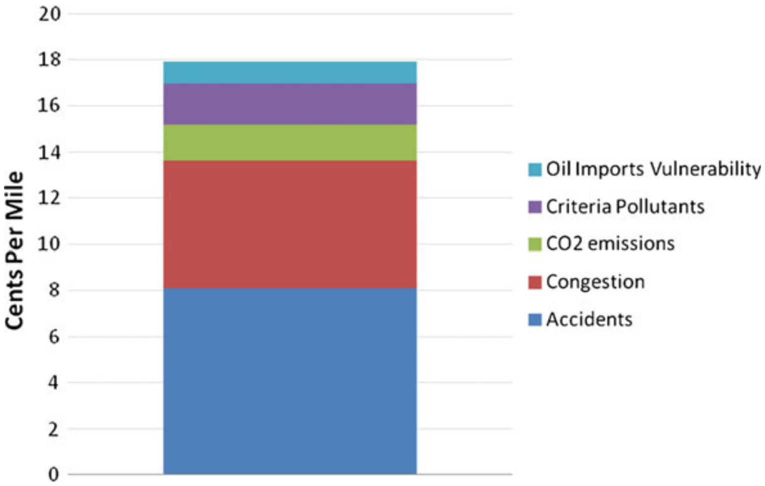

Fig. 2 External costs of driving per mile (2015 cents/mile). *Sources* [1, 13] and author's calculations

conventional vehicles *in situations that have high external costs* then they may have significantly higher external costs per mile. This is likely to be the case for driving in congested areas or times of day. As noted above, one of the advantages of CAVs is that they lower two aspects of TTC with respect to congestion: the value of time costs while in congested traffic and the premium that people are willing to pay to reduce the effort of driving in congested conditions. Both of these effects will, all else equal, make it more desirable and likely to have CAVs driving in congested conditions. This will impose external costs on non-automated vehicles. Advocates of CAVs, to the contrary, often envision a future where all vehicles are automated or in which CAVs drive in special CAV-only lanes.

The experience of high-occupancy-vehicle (HOV) lanes that are common in congested urban areas may be instructive. Their purpose is to encourage more efficient use of highways by increasing the number of passengers travelling per road mile and reducing the number of vehicles in non-HOV lanes. While some HOV lanes have been proven effective, others are found to be underutilized, because carpools account for only a small proportion of total vehicle travel and not all carpoolers use HOV lanes [32]. High occupancy and toll (HOT) lanes allow for single-occupancy vehicles (SOVs) drivers to pay a toll use using HOV lanes. HOT lanes have been adopted by the Los Angeles, San Diego, Houston, Salt Lake City, Denver, and Minneapolis-St Paul metropolitan areas, and many other cities are considering introducing HOT lanes [33]. While HOV lanes can be seen as a sorting mechanism to sort out travelers with different carpool organization costs, HOT lanes can further sort out travelers with different congestion costs [33].

Using a model that ignores the heterogeneity in travelers' congestion costs, Konishi and Mum [33] show that the welfare effects of HOV and HOT improve the social welfare in some cases, but aggravate the situation in others. While HOV lanes encourage carpooling, reducing the total traffic, they can also cause distortion from the difference in congestion levels between HOV and non-HOV. Also, if HOV lanes are converted to HOT lanes this allows single occupancy vehicles in HOV lanes to have an adverse effect by discouraging carpooling. They find, depending on the specific case, that converting HOV lanes to HOT lanes may reduce social welfare. This is likely to also be the case with dedicated CAV lanes. In some cases we will see improvements in traffic volume and flows (platooning, traffic smoothing). In other places, dedicated CAV lanes will make traffic worse for non-automated drivers. Further, despite the optimism for CAVs, non-automated vehicles and CAVs will likely share the roadway for the foreseeable future unless governments are prepared to require that individuals forego active driving.

5 External Costs of Driving and CAVs

The optimal charge for driving requires road users to pay all use and external costs of driving. This includes the costs of road infrastructure, environmental impacts, noise, accidents, and congestion. Parry and Small [22] find that the optimal US gasoline tax is $1.01/gal ($2010) (more than twice the current rate) and that the congestion externality is the largest component of the optimal fuel tax followed by a term that accounts for tax distortions, and then accidents and local air pollutants, with climate change impacts only having a minor component of the tax.

These estimates are not likely to be the same for CAVs since, depending on location, the congestion impacts of CAVs could be larger than convention vehicles. CAVs are likely to have the same per-miles costs with respect to environmental impacts, higher infrastructure costs and lower accident costs. A review of the literature by Lindsey [34] finds that while economists do agree that highway congestion should be solved by pricing, they disagree over how to set tolls, how to cover common costs, what to do with any excess revenues, whether and how “losers” from tolling previously free roads should be compensated, and whether to privatize highways.

In charging for externality costs of congestion there are two perspectives on how to set up an optimal and “fair” system. One way is to simply charge all vehicles the same cost per mile and let vehicle drivers optimize where and when to drive and which type of vehicle to drive. The other perspective is to recognize that CAV drivers face a lower cost per mile of disutility from driving and adjust per mile charges to account for this difference. This latter approach aims to take equity considerations into account: to not let CAVs impose disproportionate costs on conventional vehicles from congestion externalities.

As noted by Parry [22] the framework for designing congestion taxes is well developed, in that we know, in principal, the potentially important factors including network effects, bottlenecks, existing HOV lanes, time of day, marginal external costs and so forth. The best policies will need to be assessed on a case-by-case basis calibrated to local traffic flows, speed-flow relations, and behavioral responses to tolling. Since TTC differs greatly among drivers the best pricing scheme is not a uniform toll across all lanes, but differentiated tolls that allow drivers to sort themselves into more or less congested lanes.

Raising gasoline taxes to account for their external impacts is politically difficult. Mileage charges are increasing be seen as a promising alternative to fuel charges [35, 36]. Mileage charges, while raising privacy concerns, maybe much more tractable with connected vehicles since the real time monitoring necessary for better routing will make collecting accurate spatial and time-of-day vehicle use relatively simple.

6 Final Comments

The advent of highly automated vehicles is exciting to those who see the benefits in terms of safety, access by elderly and the handicapped and for those who view the act of driving as tiring or taking away from other activities. Contrary to some of the optimistic literature on CAVs, there may be some significant unintended consequences to their use. The two areas most clearly of concern are additional rebound driving due to the lowering of TTC. This may lead to increases in low density development and longer, but less costly commute times. Perhaps the growing use of mobility services such as Uber and Lyft and will provide insight into these outcomes.

A second area of concern is the impact of CAVs on congestion in areas of mixed traffic where CAVs operate with non-automated vehicles or pedestrians and bicyclists. There is the potential for some routes to get more congested (because the cost of congestion is less to drivers of CAVs) which will impose costs on non-automated drivers. If automation increases the prevalence and use of CAVs relative to connected or non-connected conventional vehicles in situations that have high external costs then they may have significantly higher external costs per mile. This is likely to be the case for driving in congested areas or times of day. Alternatively, in some areas, superior route and traffic flows from connectivity and synchronized driving may lower congestion and increase route capacity.

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