Assessing the Long-Term Effects of Autonomous Vehicles: a speculative approach

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Abstract

In recent years, self-driving cars have generated significant attention and discussion. While it is recognized that a number of technical and legal issues need to be solved, widespread adoption of self-driving vehicles is increasingly considered to be inevitable. However, the long-term effects of this technology are rarely considered and seldom examined in the literature. Among these potential impacts are a number of direct and indirect, positive and negative outcomes, and the net effect in terms of societal benefit or harm is far from clear. In this paper, we identify the several of these outcomes, and we explore conditions in the broader transportation system under which self-driving vehicles may be either harmful or beneficial. We investigate how autonomous operation could affect the attractiveness of traveling by car, how this in turn could affect mode choice, and how changes in mode choice would affect the broader transportation system. The paper considers three speculative scenarios, defined primarily by different behavioral responses to the availability of autonomous driving. The scenarios build on an established system dynamics model that represents the major forces involved in transportation systems. A wide range of outcomes are considered, and potential policy interventions are discussed.

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1. Introduction

Autonomous vehicles (AVs, often referred to as “self-driving cars” or “fully automated vehicles”) are widely expected to play a major role in transforming our mobility systems in coming years. The expected benefits of this technology are numerous: For example, it is predicted that autonomous systems can result in far safer operation and improved efficiency of traffic flow. Furthermore, people who use these vehicles could use their commuting time much more productively and pleasantly. Also, those previously unable to drive, due to age or infirmity, could gain access to the same level of mobility as today’s car drivers (Hayes, 2011, Fagnant & Kockelman, 2013, Anderson et al., 2014).

With such promises, substantial effort has been exerted analyzing the technical and institutional prerequisites to deployment of AVs. However, there has been very little formal research addressing potential system-wide and longer-term effects of AVs. Most of the attention devoted to longer-term effects has taken the form of speculative, informal discussion, usually focused on one or two issues in isolation (e.g., workforce changes, sprawl, etc.).

Our paper aims to identify some of the effects of vehicle automation at the system level. We focus in particular on those reactions that may only become apparent when the entire system is considered and longer-term, indirect effects are included. To grapple with the uncertainty inherent in this subject, we use a scenario-analysis approach, and employ structured qualitative methods to develop conceptual system dynamics models. While considering the potential benefits of AVs, we ask how behavioral changes made possible by AVs might affect traffic volume and congestion, land use, and mode choice behavior. Building on this holistic view, we suggest policy recommendations to encourage desired outcomes.

2. Related Work

Much of the material published on AVs to date—in both the academic and popular press—addresses specific issues, often in isolation. For example, many studies have examined the effects of AVs on the efficiency of traffic flow (e.g., Ioannou & Chien, 1993, Fagnant & Kockelman, 2013) or their impact on safety and car sharing (e.g., Pavone, Smith, Frazzoli, & Rus, 2012, Spieser et al., 2014). To a lesser degree, there has been some attention paid to less-quantifiable effects, such as behavioral changes, effects on attitudes about public transit, changes to land-use, and the impact on urban and regional planning (see Coughlin & Yoquinto, 2015, Brustein, 2014, Madrigal, 2012, Chin, 2014).

Most papers, however, only address one or at most a few issues in relative isolation. Reports that provide a more holistic approach are rare. Anderson et al. (2014) offer a summary of the potential benefits and perils of AVs, covering immediate effects of the technology, including safety, mobility for underserved populations, congestion and “costs” of congestion for users of AVs, energy use and pollution. This work also includes a brief discussion of potential effects on land-use, including both the dispersion of destinations due to increased willingness to travel and increases in urban density in some places due to the reduced need for parking. Fagnant & Kockelman (2013) also summarize some of the expected benefits of AVs, including safety improvements, which they suggest could offer reductions in fatality rates of up to 99%, and improvements in congestion, due to “shorter headways, coordinated platoons, and more efficient route choices.”

Using analytical and simulation models, Burns, Jordan, & Scarborough (2013) explore a “new mobility system” based on shared, driverless vehicles. The report finds significant economic, environmental, and consumer benefits, suggesting that such an approach could “provide better mobility experiences at radically lower cost.” In similar vein, Spieser et al. (2014) and Fagnant & Kockelman (2014) show in two case studies that a shared-vehicle mobility system can satisfy the mobility demand of a city with significantly less vehicles while causing more travel for rebalancing the fleet.

Townsend (2014) and Milakis et al. (2015) use scenario-approaches to examine the implications of AVs. Milakis et al. focus more on the traffic and transportation planning implications of AVs. Their scenarios are defined along the dimensions of technological development and policies. Townsend draws four scenarios, considering different forces shaping the adoption of AVs, the resulting impacts on land use and transportation, financing schemes, and the role of planning. The vastly different outcomes of these scenarios highlight how little is actually known about how AVs will be used and how they will affect the overall system.

Research on the longer-term effects of AVs can be broken into two key categories. On the one hand side, there are rigorous analyses based on narrow sets of data. Those typically result in well-supported outcomes, but the results are
limited to very narrow topics. Secondly, there are speculations on a broader set of issues. Those speculative discussions and analyses rarely build on existing models or frameworks of the transportation system as we know it. The resulting predictions, therefore, are difficult to connect to existing dynamics and mechanisms. Also, the interplay of indirect effects, system interactions and feedback loops have not been considered yet—although they may have tremendous impact. For example, some studies suggest that AVs might increase vehicle kilometers travelled (VKT) and this might result in increased sprawl (Fagnant & Kockelman, 2013). However, it is not acknowledged that increased sprawl, in turn, will also put further upward pressure on VKT, creating a “vicious cycle”.

The purpose of this paper is to identify such indirect effects, system interactions and feedback relations and thus to improve the understanding of the potential effects of AVs especially on user behavior, traffic volume and congestion, land use, and public transit.

3. Method

In order to identify potential effects of vehicle automation at the system level, we build our work on an established transportation base model, which describes known relations between a broad set of variables. Building on that, we used qualitative interviews and workshops to investigate how this base model will change in different scenarios of AV introduction. This section describes the modelling and data collection, the scenario development and briefly introduces the base model.

3.1. Modelling and Data Collection

As a tool to investigate effects of vehicle automation on a systems level, we have chosen to use system dynamics, an approach used to analyze complex, dynamic systems (Forrester, 1958). At its core is a mapping process, which identifies key variables and the causal relationships among them. By considering many variables in a system at once, instead of focusing on relations between just a few, system dynamics can help to build “a better understanding of the complex transportation system problems” (Abbas, 1990, for further discussion of the use of system dynamics to model problems in transportation see Shepherd, 2014).

Because we focus on the relationships among variables and the overall structure of the system, our work is limited to the use of causal loop diagrams (CLDs). CLDs can help to identify key variables and causal relationships. They make perceived system structures visible—and thus open them for analysis, discussion, and opinion making (Shepherd, 2014). One of the benefits of CLDs is that they can generate valuable insights before the relevant system behaviors can be observed or measured. They shed light on the systemic implications of known or hypothetical relationships by revealing the structure and potential behaviors that they entail (Forrester, 2007).

CLDs consist of only two main elements: variables, which are indicated by their names, and causal links, which are indicated by arrows pointing from the independent variable to the dependent variable. Causal links have positive or negative polarity, indicating the nature of the relationship—e.g., a link from variable A to B with positive polarity means that an increase in A will cause B to be larger than it would be without A’s impact. Marks can also be added to causal links to indicate delays. Once CLDs are assembled, “loops” will arise when the causal links from one variable connect back to itself, after connecting to other variables (Sterman, 2000). These loops play an important role in system dynamics modelling, so it is important to identify them and understand the role they may play in the overall behavior of the model.

The structure of system dynamics models is largely based on qualitative data (Forrester, 1968, Luna-Reyes & Andersen, 2003). In order to add formality to our data collection, we used the most common qualitative techniques: interviews and group workshops (Babbie, 2014, Vennix, 1996). We conducted semi-structured interviews and workshops with 30 individuals, with expertise in a range of fields, including transportation-planning, the automotive industry, the sharing economy, urban planning, and government policy.

In these sessions, we presented a base model (Fig. 1) that describes key aspects of current mobility dynamics and we asked the participants to suggest changes that might be caused by the introduction of AVs, and to identify how they might affect the structure of the model. With each session, we analyzed the collected information and used the results as input for further sessions (Luna-Reyes & Andersen, 2003). The summarized results are represented in the models shown in section 4.
3.2. Scenario Development

Given the amount of uncertainty in the potential effects of AVs, we chose to apply scenario-analysis methods (Schwartz, 1991, Wilkinson & Kupers, 2013). Rather than trying to determine the most likely outcomes, this approach aims to develop useful insights by exploring a range of different futures. It tries to identify the main forces that will affect outcomes in question, followed by speculation about the development of these forces. To counter the inherent subjectivity of this process and steer our analysis toward more objective outcomes, we used interviews and group discussions with a diverse group of people with widely varying perspectives.

As the public discussion at the moment rarely questions if AVs will become a reality—but focuses more on when they will be available—we assumed in our scenarios that AVs are successfully developed and fully adopted. Technological challenges, legal obstacles, factors that may spur or hinder adoption, and the adoption process itself were not subjects of our study.

Based on existing literature (Jonas et al., 2015, Townsend, 2014) and our interviews and workshop discussions, two major dimensions of uncertainty emerged that seem to drive the outcomes of vehicle automation on a system level: How will travel behavior change due to this technology and how will behavior regarding ownership change? In other words: Are people going to use cars in the same way as they use them today or will existing behaviors change? Will people still primarily own their own private vehicles or will mobility become a service? Based on these dimensions, we developed three scenarios that are described in Section 4.

3.3. Baseline Model

To investigate the effects of vehicle automation, we used an established CLD of traffic and congestion developed by John Sterman (2000). At the core of this model is the question of how to reduce road congestion. As in other transportation models (e.g. Egilmez & Tatari, 2012, Pfaffenbichler et al., 2010), this CLD considers road capacity, trip generation, land use, mode choice and public transit. Sterman’s model specifically considers the effects of a common policy intervention to congestion: road building. The model makes an appropriate framework for discussion as AVs are widely considered as a way increase road capacity, which can theoretically be accomplished due to closer following distances possible with connected AVs.

In Sterman’s model (Fig. 1), Attractiveness of Driving plays a central role. It is a function of Travel Time, Desired Travel Time, Public Transit Fares, and Adequacy of Public Transit. Attractiveness of Driving then plays a key role in a number of dynamic effects that balance out the benefit achieved by road building: it increases Trips per Day, Average Trip Length, and the Number of Cars in a specific region. All these factors tend to balance out the effect of road building, and suggest that the system will settle out at a new equilibrium state with potentially no improvement in congestion, but higher VKT.

As road/highway capacity expands, people are able to travel farther in less time, so the Size of the Region that can be reached within a Desired Travel Time increases (and density of origins and destinations falls); this reduces the Adequacy of Public Transit; this further increases the Attractiveness of Driving, which means fewer people ride transit; fewer people riding transit means less revenue and poorer service. As a result, the number of people riding transit decreases even further, which in turn leads to more people driving.
Fig. 1. The baseline model (Sterman, 2000)
4. Introducing Autonomous driving: Effects in Three Scenarios

In the following sections, we discuss three scenarios for a future mobility system with AVs (see section 3.2). In each section, we first describe the scenario. We then explain the major changes that we made to Sterman’s model to reflect the assumptions of each scenario. All of our scenarios assume complete adoption of AVs, including the benefits of connected-vehicle technologies.

4.1. Scenario 1: Technology Changes, But We Don’t

Scenario description: This scenario assumes no change in behavior or in ownership. AVs are used in the same way as cars are used today and vehicles are privately owned. Expected improvements (e.g., our interview subjects presumed that “driving will be so much safer,” or “my commute will be so much more pleasant”) do not lead to any behavioral changes.

Modifications to existing model: The fundamental assumption of this scenario is that behavior regarding travel choices will not change with the introduction of AVs—i.e. the number of trips, distances travelled, and mode choice stay the same. To reflect that assumption, we do not consider any additional effects of Attractiveness of Travelling by Car in our model. We do, however, allow increases in Trips per Day per Car and Cars per Person, caused by the increase in Mobility for those Unable to Drive. We consider AVs as a way to increase road efficiency. Thus, Pressure to Increase Efficiency of Traffic Flow replaces Pressure to Reduce Congestion and Efficiency of Vehicle Operation replaces Road Construction. We also renamed and inserted some variables and links for clarification (Travel Time as inverse of speed, Attractiveness of Travelling by Car instead of Attractiveness of Driving; introduction of Congestion, Dispersion of Origins/Destinations; link between: Dispersion of Origins/Destinations and Adequacy of Public Transit).

We further introduce expected effects of AVs: Efficiency of Vehicle Operation, Safety of Vehicle Operation, Mobility for Those Unable to Drive are assumed to increase while Attention Needed for Driving is going to decrease (Fagnant & Kockelman, 2013, Anderson et al., 2014). These effects have further consequences: Increased Efficiency of Vehicle Operation increases Highway Capacity and will reduce Energy Consumption. This, in turn, will decrease Pollution and Energy Expenses. Lower expenses will increase the Attractiveness of Travelling by Car. Increased Safety of Vehicle Operation, i.e. less accidents, will not only reduce congestion but also make travelling by car more attractive. Improved Mobility for Those Unable to Drive leads to more Trips per Car per Day and to an increased number of cars.

Expected system-level outcomes: In the case that AVs do not cause a change in people’s behavior, a lot of benefits on a system level can be expected compared to our current mobility system. Travelling by car will be safer, cheaper, less energy consuming, more environmentally friendly, and a lot of time spent in the car can be used in a better way. Also, the situation of millions of people who currently have limited access to mobility would improve. Although these new traffic participants will increase traffic volumes, it can be assumed that this effect could be offset by the increased efficiency of vehicle operation and traffic flow.

4.2. Scenario 2: New Technology Drives New Behavior

Scenario description: In contrast to Scenario 1, this scenario assumes major changes in behavior related to travel and use of vehicles, but it assumes no change in ownership choices. Individuals and businesses discover new uses for cars and people are willing to take more and longer trips than they did in their conventional cars. For example, our interview subjects observed: “I could work in my car, so I wouldn’t have to stay so long at the office,” and “I could live farther away”.
Fig. 2. CLD showing changes to the baseline model resulting from assumptions of Scenario 1

**Modifications to existing model:** Based on the assumption that people’s behavior will change due to the introduction of AVs, we now consider effects caused by an increased *Attractiveness of Travelling by Car*. In our
model, this increase will lead to more *Trips per Car per Day* and higher *Average Trip Length*, as well as lower levels of *Public Transit Ridership*.

Fig. 3. CLD showing changes to the baseline model resulting from assumptions of Scenario 2
We assume that increased Comfort & Utility of Time in Car leads to a higher Acceptable Travel Time. We also include variables to represent potential new behaviors: Trips with empty vehicles will be possible. This might not only lead to less parking traffic, but also to additional trips in the form of Empty Vehicle Trips to Avoid Parking. Overall, this will make driving by car more attractive. New Uses for Cars become possible with AV technology, such as sending your car to run errands for you, so it can be expected that the number of Trips per Day per Car and the Cars in Region will increase.

**Expected system-level outcomes:** AVs will increase the attractiveness of travelling by car, causing a major shift in travel behavior. As discussed in section 3.3, increasing Attractiveness of Travelling by Car triggers dynamics within the system that will lead to a new equilibrium with higher traffic volumes at a similar level of congestion and with a decreased public transit ridership. There will also be upward pressure on traffic volumes due to the growth in Trips per Day per Car and Cars in Region that can be expected to result from New Uses for Cars. Apart from that, these dynamics will drive the effects on land use and public transit discussed in Section 3.3: people will be willing to drive longer distances, which will increase sprawl and make it more difficult to provide adequate transit services. Overall, the structure of these dynamics suggests potentially much higher levels of VKT with its consequences and a risk of devastating effects on land use and public transit.

### 4.3. Scenario 3: New Technology Drives New Ownership Models

**Scenario description:** This scenario builds on the behavioral changes of Scenario 2, but also assumes complete change in ownership: It examines a case where all vehicles in operation are shared AVs. Multiple reasons could cause the shift to shared vehicles—e.g., increased appeal of vehicle sharing as vehicles can drive where they are needed, lower prices due to higher vehicle utilization, or enforcement by cities that ban private cars from certain areas.

**Modifications to existing model:** As many people share one car, the adoption of shared AVs will increase the Utilization of Vehicles, and thus the Trips per Day per Car. It will reduce the number of Cars per Person and due to higher utilization reduce the Fixed-Costs per Trip. This cost reduction will make travelling by car more attractive. On the other hand, vehicle-sharing leads to increased Price Transparency as its per-trip-payment exposes many of the hidden costs of driving that most people usually do not consider. This transparency has the potential to reduce the Attractiveness of Travelling by Car. The AVs capability to drive while empty allows for redistribution of vehicles to better match supply and demand, and ensures that cars are available where and when they are needed. Rebalancing will increase the number of Trips per Day per Car.

**Expected system-level outcomes:** While vehicle sharing reduces the number of cars in the region, it also leads to higher utilization of cars and thus more trips per car per day. Overall, it can be expected that traffic volumes and VKT are going to increase compared with the current state, due to rebalancing trips and new behaviors. Benefits could result from parameters not modeled here—e.g., newer vehicles on the road, increased fuel efficiency of AVs, and more appropriate vehicle choices for different uses.

But the vehicle sharing scenario comes with more interesting effects. The cost of driving not only depends on the individual user, but also on the structure of demand and supply of the vehicle sharing system. In other words, the greater the imbalance between demand and supply in an area, the more empty rebalancing trips are needed, and the more vehicles are required in a fleet to fulfill all travel requests. The number of empty trips and idle vehicles will influence the per-mile cost for all users and thus influence the Attractiveness of Travelling by Car. This means per-mile travel costs in small, dense areas will be lower than in sprawled-out areas. This would fundamentally change the current cost-structure of driving in which driving becomes cheaper per mile the more someone drives. Travel cost also influence the Size of the Region within Acceptable Travel Cost. Vehicle sharing could lead to a new balancing effect: as other factors in the model encourage sprawl, the demand/supply imbalance in the region grows, which increases per-mile costs and total trip costs, which reduces the size of the region within acceptable travel costs, which puts downward pressure on sprawl. This could then drive some of the reinforcing effects of public transit: if vehicle sharing reverses sprawl to some degree, then public transit may even gain attractiveness, resulting in higher ridership, which over time translates to better service, and fewer trips taken by car.
Fig. 4. CLD showing changes to the baseline model resulting from assumptions of Scenario 3
5. Conclusion

The scenarios examined here illustrate a variety of potential outcomes from the adoption of AVs. They are not meant to describe an exact picture of the future but rather show a range of possible futures. In all three scenarios, driving will become safer, time spent in the car can be used differently, and the situation of people with limited access to mobility would improve. Furthermore, the per-mile-cost and energy consumption would decrease. However, our models show that not all the effects would be desirable: In all three scenarios, VKT is likely to increase, leading to a potential increase in energy consumption and emissions. The level of increase, however, appears to differ significantly among the scenarios.

Scenario 1 shows that if the people’s behavior does not change, AVs will most likely lead to better outcomes than our current mobility system. If, however, behavior changes occur as depicted in Scenario 2, AVs increases the attractiveness of travelling by car and, as a consequence, traffic volumes will rise significantly. This leads to a higher equilibrium-level of congestion, with substantially higher levels of VKT. Also, sprawl would be further encouraged, and public transit would become less and less adequate. In this scenario, AVs will not contribute to a more sustainable mobility system but will likely put additional stress on traffic systems that in many areas are already performing at their limits.

The results of Scenario 3 are less clear: in a purely shared AV scenario, the number of cars would decrease, which can create positive outcomes as less parking space is needed. At the same time, however, the traffic volume and VKT are even higher than in Scenario 2 due to rebalancing trips. This scenario suggests additional ambiguities in terms of cost, which again affect the attractiveness of travelling by car. Costs are likely to decrease due to higher vehicle utilization, but prices will become more transparent, which will make travelling by car appear more expensive. Furthermore, the current cost-mechanics of driving would change, to favor short trips in dense areas, eliminating the current per-mile-cost-advantage of long car trips. The cost structure of vehicle sharing could also counteract sprawl and thus make public transit a more adequate mobility option. This phenomenon could be supported by additional factors that we have not considered in our models: shared AVs could have a role in strengthening transit by acting as feeders providing first- and last-mile connectivity to trunk lines, supplementing existing service, and potentially replacing high-cost, underutilized routes. This could improve the accessibility and appeal of public transit. We also did not address the potential role of ride-sharing in shared AVs, which could have a substantial effect in very dense areas, where users may only have to slightly alter their travel plans to share rides with other travellers.

The analysis of our three scenarios provides strong indication that the introduction of AVs alone cannot solve the problems our current mobility systems are facing. When aiming for a greener, more sustainable future for transportation, we have to consider this new technology and its broad impact on a system level. The models we developed suggest several starting points for policy interventions that could help to steer the system towards more desirable outcomes.

To reach those desired outcomes, it may be essential to develop ways that reduce the Attractiveness of Traveling by Car, increase the Attractiveness of Public Transit, discourage urban sprawl, limit the amount of driving that people can do (a form of rationing), or some combination of these. With regard to our model, this approach can be broken down into several categories, many of which are already quite familiar in transportation planning circles: (1) increasing financial costs—e.g. through road use charges or tiered road-pricing mechanisms that would allow a base level of low-price road use, followed by increasing rates with higher levels of driving; (2) increasing travel time—e.g. by new speed limits or lower road throughput; (3) limiting the comfort and utility of time in car—e.g. by requiring that at least one passenger pays full attention to the road; (4) making transit and other modes more attractive and/or encourage use of AVs to connect to transit; (5) regulating land use to discourage long commutes and encourage other modes; (6) restricting driving—e.g. restrict the amount of driving each individual can do, prohibit private empty car trips, limit to certain uses or only allow rides that connect to or from transit stops.

Finally, as we consider potential research and policy interventions, we believe it is important to keep in mind that taking a “wait and see” approach with AVs can come with serious consequences. By the time there is a critical mass of AVs in use, it may be too late to impose corrective measures. On the other hand, pro-active action can help to shape a framework for AVs to become an integral part of a more sustainable transportation system we envision. For example, it may be possible to get AVs widely accepted as shared-use vehicles and public transit tools, before they become entrenched as a new form of private personal mobility. Our models and scenarios have identified some powerful forces
that may come to play on the dynamics of our transportation system—and thus provide a valuable starting point for future policy discussions. AVs are a promising technology, but to leverage their potential, we have to launch the public discussion about the desired—and undesired—long-term outcomes of their use right now.

References


