Forecasting the Impacts of Autonomous Vehicles

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Humanities and Arts Course Sequence:

Course Number	Course Title	Term
PY 1731	Introduction to Philosophy and Religion	D – 2015
PY 2731	Introductory Ethics	A – 2015
PY 3731	Problems in Ethics and Social Philosophy	B – 2015
WR 1011	Writing About Science and Technology	C – 2016
HU 2230	Culture and Place: Unraveling Russia's Riddles	E – 2016
HU 3900	Philosophy and the City: Urban Humanities	A – 2017

Presented to: Professor Bethel Eddy
Department of Humanities & Arts
A-Term – 2017
HU 3900 A03

Submitted in Partial Fulfillment of
The Humanities & Arts Requirement
Worcester Polytechnic Institute
Worcester, MA

Introduction

Autonomous vehicles (AVs) have rapidly transformed from a science-fiction topic to an impending reality. Erick Guerra, of the Department of City and Regional Planning at University of Pennsylvania, postulates that commercial level AVs will be available in the next 20 years (Guerra 210). Todd Litman, of the Victoria Transport Policy Institute, predicts that AVs will be "common and affordable" in the 2040s to 2060s (Litman 1). Tim Chapin et al. went as far as to say that "The impact of AVs … may be of a magnitude similar to those during the rise of the private automobile in the early 20th Century" (Chapin et al. 2).

Given that many experts in transportation and urban planning recognize the imminence of AVs, it is important to make predictions about their effects in order to prepare our cities for their arrival. However, predicting the effects of AVs has proven very difficult. A member of one Metropolitan Planning Organization (MPO) said that planning for AVs is like "pondering the imponderable" (Guerra 214). This is partly due to the fact that there are a high number of volatile possibilities, which are in turn dependent on elements which are difficult to observe. For example, many of the effects of AVs will depend on the rate of adoption of AV technology (in other words, how quickly consumers purchase cars with AV technology). However, this is, in turn, dependent on how quickly AV technology is developed and how quickly it becomes affordable for consumer-level vehicles.

One particularly interesting problem is the expected effect of AVs on roadway congestion. It is interesting for two reasons: first, roadway congestion is a colossal problem; second, it is extremely difficult to make predictions about due to competing factors, some of which could increase roadway congestion, while others could decrease roadway congestion.

The authors of an urban mobility report estimated that 5.5 billion hours of time and 2.9 billion gallons of fuel were wasted in 2012 due to congestion (Schrank, Eisele and Lomax 5). They also found that the costs of congestion are increasing. The report states that congestion cost the average commuter $818 in 2011, as opposed to $342 in 1982 (adjusted for inflation) (Schrank, Eisele and Lomax 5). The time costs don't just affect rush-hour commuters either; Schrank et al. found that "37% of the total delay occurs … outside of the peak hours" (Schrank, Eisele and Lomax 5).

The effect of AVs on congestion is so difficult to predict primarily because many of the influencing factors are difficult to predict. Erick Guerra interviewed representatives at several MPOs across the US. In his report, he recalls that "Most interviewees saw significantly higher and significantly lower [vehicle miles traveled][1] as potential outcomes." (Guerra 214) Thus, the conclusion one draws can be highly sensitive to the types of data and predictions consulted, and the significance attributed to each influencing factor.

While AVs will certainly introduce situations which will both increase and decrease roadway congestion, there is convincing evidence that the net effect of AVs will be to reduce overall congestion. This paper attempts to develop a rigorous argument by utilizing projections, simulations, and case studies created by a diverse sample of experts.

The organization of this report is as follows. First, we will analyze the effects that the automobile has had on the city. Next, we will discuss the transition from human-operated vehicles to fully autonomous vehicles. After that, we will consider the expected effects of AVs on roadway design, while considering the ethical concerns that may arise. We then reflect on the

[1] Vehicle miles traveled (VMT) is the total number of miles traveled by all vehicles in a set region in a set amount of time. (Federal Highway Administration, par. 5)

topic of roadway congestion in general, before investigating the possible impacts of AVs on congestion.

The (Human-Operated) Automobile and the City

Before discussing AVs, it will be useful to reflect on how human-operated vehicles shaped the city during the 20th Century. Historians identify three primary stages in the history of automotive technology: the Walking City, before 1880, the Streetcar City, from 1880 to 1920, and the Automobile City, from 1920 to present (Melosi (2), par. 1).

During the time of the Walking City, most travel was by foot. Long distance travel was done on horseback or some horse-powered vehicle. Consequently, cities were highly compact, with most people living very close to where they worked (Melosi (2), par. 2). The design of streets was also heavily influenced by the primary modes of travel. Streets were narrow, windy, and unpaved (Melosi (2), par. 2). The introduction of the streetcar began to allow upper and middle class families to move out of the cities and into suburbs (Melosi (2), par. 3). However, people could still only travel on pre-defined routes.

It wasn't until the advent of the automobile that suburbanization really took off, as the automobile allowed people to travel places streetcars couldn't go. The automobile required significant changes to the design of city streets and the city itself. Streets needed to be paved, signs and signals needed to be added to orchestrate automobile and pedestrian traffic, and space for parking, both in lots and on the side of the street, was needed. Today (2017), it is estimated that half of the land in cities is dedicated, in some way, to the automobile (Melosi (1), par. 1). This includes roads, parking, service stations, and car dealerships (Melosi (1), par. 1).

If nothing else, the automobile revolutionized personal transportation, allowing people to travel farther and faster than they ever could before. However, most historians recognize the significant drawbacks of the automobile. As Frederick Stout said, “The common wisdom seems to be that automobiles were one of those technological mistakes of modernism that have had an overwhelmingly negative effect on the course of human development.” (LeGates and Stout 699) While many people enjoyed the ability to move into more affordable, and less crowded, housing in the suburbs, some found that the coherent organization of the compact walking cities was destroyed (Melosi (2), par. 6). Also, the automobile took over the majority of the space on roadways. Pedestrians were relegated to sidewalks, although on many roads, pedestrians were left with little or no space at all.

The automobile introduced several ethical concerns, which could persist or grow worse under autonomous vehicles. Suburbanization, by increasing total vehicle use, could increase carbon emissions and harm the environment. We must consider if it is ethical to encourage this lifestyle. Also, the majority of space in the city is used by automobiles (Melosi (1), par. 1). If it is possible for AVs to consume even more space, we must contemplate if it is ethical for this trend to continue, or if pedestrians have rights to more city space.

The introduction of the automobile to the city wasn’t wholly positive or negative. However, it is important to reflect on the effects of the automobile to begin planning for the effects of AVs.

The Transition from Human-Operators to Full Autonomy

The transition from fully human-operated cars to fully autonomous cars won’t happen overnight. Rodney Brooks, a roboticist and Professor Emeritus at MIT, discussed how Amara’s Law applies to AVs:

> Amara’s Law is this: we tend to overestimate the effects of technology in the short run and underestimate it in the long run … We’re going to see driverless

> cars come, slowly over time, slowly at first, in restricted environments, and fifty years from now, [humans will not] be allowed to drive cars. (Brooks 1:45-7:00)

The majority of cars on the road today have some semi-autonomous features, like cruise control, which reduce the rote tasks required of the driver, but still necessitate the driver to pay attention to vehicle operation at all times. More advanced semi-autonomous features can be found in new, high end cars, such as the 2016 Lincoln MKS, and 2017 Mercedes-Benz E-Class, which both come with automatic parking systems (Krome 2-3). Vehicles which can operate fully-autonomously under pre-defined conditions are currently in development, with Tesla's Elon Musk claiming that Tesla will develop and test drive such a vehicle by the end of 2019 (Lambert, par. 7).

There will be a transition period during which human-operated and fully autonomous vehicles will share the road. However, as Litman stated, "most impacts, including reduced traffic and parking congestion … will only be significant when autonomous vehicles become common and affordable … and some benefits may require prohibiting human-driven vehicles." (Litman 1) Thus the majority of this paper will focus on the effects of fully autonomous vehicles[2], while largely ignoring the dampening effect human-operated vehicles will have on the benefits of AVs.

Impacts of AVs on Roadway Design

To understand the effects of AVs on roadway congestion, it is important to first understand how AVs will necessitate changes to the design of the city during the transition from human-operated vehicles to AVs.

Most experts agree that, in order to allow for a comfortable transition from human-operated vehicles to AVs, it will be necessary to designate AV-only lanes, particularly on

[2] In general, by "AV", I mean a fully autonomous vehicle.

highways (Litman 14). High-occupancy lanes (HOV) could easily be transformed into AV-only lanes, using an EZ-Pass-esque checkpoint to ensure that all entering cars possess the necessary technology (Malesci, par. 5). This will permit AVs to operate without concern for human-operators, while allowing passengers to reap many of the benefits of autonomous driving before AVs reach full market penetration. However, these lanes will have to be added carefully in order to minimize disruptions to human operators. When fully autonomous vehicles are first commercially available, they will only be accessible to the wealthy. It isn't fair to human operators to suddenly take away all of the HOV lanes and increase their commuting time if they can't afford an AV.

It is commonly expected that AVs will allow for more narrow lanes. Lanes are currently much wider than the vehicles in them to give room for human-operators to "sway" left-to-right within the lane. AVs will drive much more precisely than humans can, so this space will not be necessary (Chapin et al. 7). Also, passenger AVs are expected to be smaller than modern cars. Even if AVs were to remain the same size as modern cars, Chapin et al. expects that lane widths could be reduced by 20% (Chapin et al. 7). To further reduce the road space used by vehicles, it is likely that most medians between lanes of opposing traffic can be shrunk or eliminated entirely (Chapin et al. 7). Within cities, this will allow more space to be dedicated to pedestrian walkways and cycling lanes. While these optimizations are technically feasible, they could make travel more dangerous by reducing room for error. Even if AVs are held to the highest safety standards, leaving such little space between AVs could allow for catastrophic accidents to occur, albeit extremely rarely. It will be important to consider the ethical implications of reducing lane widths, especially with regard to the accidents that could be generated by AVs traveling more closely together.

AVs are able to perceive the world around them through various cameras, sensors, and radar. However, it will be especially useful for AVs to be able to communicate with their environment directly. Vehicle-to-Vehicle (V2V) communication allows AVs to send and receive information about other vehicles' speeds, traffic incidents, and roadway conditions (Wedel, Schünemann and Radusch 637). Similarly, Vehicle-to-Infrastructure (V2I) communication will allow vehicles to receive the information that human-operators generally get from various signs and signals, although in a more easily understood form. New technology will be necessary to allow vehicles to receive communications from infrastructure. 3M is currently embedding barcodes in street signs which can transmit information about what can be expected ahead (Muoio, par. 3). While this form of V2I could be very helpful while humans and AVs share the road, most street signs and road markings will eventually be able to be removed, save those necessary to direct pedestrians and cyclists (Chapin et al. 13). Although some current-day AVs utilize road markings, later iterations won't need them as they will be able to rely on information from other cars and infrastructure, which instead of being on signs, could be put in devices underground (Chapin et al. 13).

As with most forms of electronic communication, a reasonable concern is the possible infringement of privacy that could occur through V2V and V2I communication. For example, is it necessary to anonymize information sent from AVs, perhaps to prevent stalking? Also, in designing smart infrastructure, we will need to consider the possibility of hackers creating and placing malicious infrastructure in cities to steal information or possibly to cause accidents (perhaps by telling two AVs that they can go through an intersection at the same time). What ethical obligations do AV manufacturers have to their consumers? If an accident does occur due to a malicious device hidden in infrastructure, where does the blame for the accident lie? There are no correct answers to these questions – instead, we will have to keep them in mind throughout the development of AVs.

V2V and V2I communication have immense potential to increase the efficiency of roadways. One situation in which they will be helpful is intersections. Currently, intersections are managed by some external signal (eg. a stoplight or sign) and associated traffic rules. However, external management of intersections is often not very efficient. For example, stopping at a stop sign when there are no other vehicles at the intersection wastes time. V2V communication will eventually enable peer-to-peer coordination of intersections. AVs will know the intentions of all other vehicles in the intersection, and will be able to cross as soon as it knows it is safe to do so (Chapin et al. 14). Optimally, this will create intersections in which vehicles never have to stop.

One concern with free-flowing intersections is their impact on pedestrian and cyclist traffic. If AV traffic never has to stop, pedestrians and cyclists could be left waiting a long time to cross the road (Chapin et al. 15). To counteract this, it may be necessary to force vehicle traffic to stop to allow pedestrian and cyclist travel as well, although more optimal, creative solutions are possible. To allow for free-flowing vehicle and pedestrian traffic, many roads in Moscow, Russia have replaced crosswalks with underground tunnels and aboveground footbridges.

Another issue is communication between AVs and pedestrians and cyclists. Humans have developed an informal system of hand-waves and head-nods to indicate that they are letting a pedestrian cross the street. Without human drivers, this communication system will erode. To combat this problem, Ford has developed a method for AVs to "communicate" with pedestrians using light signals (Ford, par. 2). They have partnered with Virginia Tech to test their system, in which a human drives the car, hidden by a "seat suit" which covers the driver's body and face (Ford, par. 6). While most pedestrians the car encountered in their study were startled at first to see no driver behind the wheel, people were quick to understand the car's light signals. Ford is currently working towards developing an industry standard for AV/pedestrian communication, which should resolve this issue.

Finally, the parking needs of AVs will be drastically different from the needs of human-operated vehicles. First, on-street parking spaces will be able to be eliminated (Chapin et al. 17). Since AVs don't require a human operator, they will be able to let their passengers out at their destination and park themselves. Furthermore, cities will be able to move most parking locations outside of the crowded city center. If parking is needed close-by (perhaps for quick trips), the amount of space used will be able to be reduced, for a few reasons. First, AVs will be able to park closer together, since there won't need to be space to allow passengers out, or to access the trunk (Chapin et al. 17). Second, parking garages won't have to accommodate the needs of humans; lighting, handicap-accessibility, and climate control will not be necessary (Chapin et al. 18). Also, AVs will be able to be double-parked, or otherwise block other cars in, since they will be able to coordinate with other AVs using V2V communication.

Congestion

Roadway congestion was and is one of the most prominent impacts of automobiles on cities (Melosi (3), par. 1). Cities that were established before the creation of the automobile weren't designed with the car in mind, so many cities had a difficult time making room for them on their roads. To combat congestion at the beginning of the Automobile City, many cities made streets wider by reducing pedestrian space, and built expressways through cities (Melosi (3), par.

1,5). However, in many cases this just scaled up the problem, as increased resources for driving and decreased resources for walking and cycling incentivized more people to drive.

The US Federal Highway Administration (FHWA) identifies two types of congestion: recurring and non-recurring (Cambridge Systematics (2), 5-4).

Recurring congestion is that which occurs cyclically over some length of time; a common example is traffic during rush hour. In general, it is when the number of vehicles on the road surpasses the road's capacity (Anderson et al. 40). The Texas A&M Transportation Institute's (TTI) Urban Mobility Report identified several measures to reduce recurring congestion. One of the most cost-effective and environmentally-friendly methods was to use current resources more efficiently (Schrank, Eisele and Lomax 17). One way to do that is to improve traffic flow (Schrank, Eisele and Lomax 19). The TTI Report found that roads with bottlenecks can only fit half to two thirds of the vehicles of that same road had the traffic been flowing smoothly (Schrank, Eisele and Lomax 19). If the existing infrastructure simply isn't enough, adding more lanes is a simple way to increase throughput[3] and thereby reduce congestion (Schrank, Eisele and Lomax 15).

A difficult, albeit effective measure to reduce recurring congestion is to change usage patterns (Schrank, Eisele and Lomax 17). Since recurring congestion is caused by too many people attempting to use a road at one time, any way to reallocate some of that traffic, either to a different time or different road, would reduce congestion. Reallocation methods can take several forms. To reallocate traffic to different roads, a GPS which is aware of traffic information (such as Google Maps or Apple Maps) could choose to redirect certain cars to one road and some cars

[3] Throughput is the number of cars able to travel through a roadway in a set amount of time.

to another. However, this introduces an ethical concern; namely, is it possible that this sort of system would discriminate, perhaps by always sending low-income drivers through more dangerous areas of the city than their wealthier counterparts? To reallocate traffic to a different time of day would require a more creative solution; perhaps companies who, by moving away from the traditional nine-to-five schedule, could reduce the intensity of rush hour traffic.

On the other hand, non-recurring congestion is that which is caused by sporadic events, such as construction, inclement weather, high capacity events (such as sporting competitions or concerts), or car accidents (Anderson et al. 40). In general, the best way to reduce or eliminate non-recurring congestion is to predict the time and location of such congestion and prepare as adequately as possible. This can be difficult due to the irregular nature of non-recurring congestion. Some manifestations of non-recurring congestion, such as high capacity events and construction, are scheduled far in advance, so they can be planned for and rerouted around. However some factors, like weather and accidents, simply can't be forecasted impeccably, and require quick solutions to minimize their effects on congestion.

FHWA states that the two types have about equal impact on total roadway congestion (Cambridge Systematics (1), ES-6). Consequently, the next two sections will discuss the effects of AVs on both types of congestion.

Benefits of AVs on Roadway Congestion

Humans are, naturally, very poor drivers. Even the very best drivers get distracted and tired. Others may text, drink, or otherwise distract or inhibit themselves from driving properly. AVs, on the other hand, never get distracted and never get tired. While they won't be absolutely perfect, they will be markedly better than humans in many ways. Some of those ways which will impact roadway congestion are discussed next.

When driving behind another car on a freeway, human operators are generally advised to follow the two-second rule (NYS DMV 63). That is, it should take two seconds for the following car to reach the car in front of it should it abruptly stop. Using V2V technology, AVs will be able to follow more closely than is safe for human operators (Chapin et al. 7). It is unclear how much closer AVs will be able to drive together, as it will be sensitive to the latency of V2V communication and the processing speed of the cars. However, one study estimated that once the large majority of cars (~90%) have Cooperative Adaptive Cruise Control (CACC), AVs will be able to utilize freeways 80% more efficiently (Shladover, Su and Lu 11). That is to say, if a section of road currently has a 10 car capacity (with necessary headway in between), CACC will allow that same section of road to fit 18 cars.

In addition to improving roadway efficiency, V2V and V2I communication will allow AVs to reroute around congestion (Wedel, Schünemann and Radusch 637). Wedel et al. found that their algorithm, in simulation, reduced average travel time by 50% when 80% of vehicles on the road utilized V2V systems (Wedel, Schünemann and Radusch 641). Interestingly, human-operated cars received a benefit as well, even though they wouldn't reroute like many of the AVs.

V2V/V2I communication will also enable AVs to predict when other vehicles will brake and accelerate, allowing them to fine-tune their acceleration/deceleration (Fagnant and Kockelman 4). This should significantly reduce the number of bottlenecks, which normally occur when a vehicle on a freeway brakes abruptly, causing a rippling effect on the vehicles behind it. This has huge potential to reduce congestion, as FHWA estimated that bottlenecks account for

40% of overall congestion (Cambridge Systematics (1), ES-6). Also, the reduction of bottlenecks should increase the efficiency of current road networks and improve traffic flow, both of which Schrank et al. identified as means to decrease roadway congestion.

AVs have the potential to eliminate human-caused accidents. Of the 5.5 million car crashes in the US in 2011, 93% had some human factor (speeding, intoxication, etc.) as the primary cause (Fagnant and Kockelman 4). Obviously this is a great thing simply in terms of lives saved. But as 25% of congestion is caused by traffic incidents, it also has a significant effect on non-recurring congestion (Cambridge Systematics (1), 2-4).

Of course, AVs won't reduce accidents if they cause more themselves, through software crashes or malfunctions, than they prevent. However, these sorts of crashes can be easily minimized. Many issues with software occur because users neglect to keep their software up-to-date. However, AVs could be designed with the restriction that they must install all available updates before they can begin driving. Also, AVs will need to have fail-safe features to ensure passenger safety. This could include a feature which pulls the vehicle over to the curb when the overall navigation system fails.

AVs can also reduce congestion by reducing the number of cars on the road. Autonomous taxis have the potential to increase car sharing, thereby decreasing the number of cars on the road (Litman 5). Uber polled their customers and found that 10% of Uber riders under 30 have replaced owning a car with using Uber (Kendall, par. 15). While this is a small fraction of commuters, it is likely to increase once the majority (or perhaps entirety) of Uber's fleet is autonomous. Since Uber won't have to pay drivers, they will be able to lower their prices and outcompete traditional taxi services. Erick Guerra suggested that Metropolitan Planning Organizations (MPOs) consider the possibility that "shared autonomous taxis [could] replace private cars and public buses, particularly in more urban areas." (Guerra 220) However, this is likely to be an extreme scenario. Many people who live in cities today are able to rely solely on public transportation and car-sharing services. However, the people who currently live in the city and own cars are unlikely to sell their car when taxis become autonomous. The only incentive would be decreased fares, but these types of people most likely own a car because they need it to travel outside of the city, at which point it wouldn't be cost effective to utilize taxis.

There are many ethical concerns with regard to providing a *shared* autonomous taxi service. That is, one in which multiple strangers share the cost of a single taxi. Without a human operating the taxi, there would be no one in the vehicle to mitigate any issues between the passengers, from simple arguments to assault and theft. An obvious solution would be to include cameras inside the taxis. However, this introduces a new dilemma; namely, when is it ethical for taxi companies to hand their footage over to law enforcement? The ethical choice may be clear in an assault case, but more nuanced in a case where law enforcement wishes to monitor a person of interest who as of yet has done nothing wrong.

Drawbacks of AVs on Roadway Congestion

AVs have the potential to increase roadway congestion in two major ways: first, by putting more cars on the road than there would have been before; second, by increasing the total vehicle miles traveled (VMT) of a roadway or region.

One way that AVs could increase the number of cars on the road is by introducing empty vehicle traffic. Empty vehicle traffic refers to any vehicles which have no human passengers. AVs will generate several sources of empty vehicle traffic. The first is autonomous taxis searching for their next fare (Litman 7). However, there's no evidence that there will be a significantly increased demand for autonomous taxis than there currently is for human-operated taxis. In fact, there will probably be a lower demand as shared taxi services (eg. Uber and Lyft) will allow multiple customers to use one taxi. Thus this shouldn't generate a significant increase of traffic.

Another source of empty vehicle traffic will be AVs searching for parking. Since AVs won't need a human to operate them, they will be able to drop off their passengers directly at their destination and park themselves (Chapin et al. 9). However, the effect on congestion will likely be isolated to the drop-off / pick-up location. As with autonomous taxis, this doesn't add any new cars on the road that weren't there already, so it is unlikely that it will increase congestion overall.

While most sources are unsure of AVs' overall effect on congestion, most are relatively certain that AVs will increase total Vehicle Miles Traveled (VMT). The FHWA defines VMT as the total miles traveled by vehicles in some region over the course of a year (Federal Highway Administration, par. 5). This region could be a particular roadway, or the entire United States.

One reason national VMT is likely to increase is that AVs will decrease the time-cost of travel (Guerra 214). In other words, the person who would've been operating the vehicle will now be free to work, relax, rest, or otherwise make productive use of their time. These benefits were always available to commuters using various forms of public transportation. However, since traveling in a personal AV would provide increased comfort and privacy over public transportation, it is likely that many will prefer to commute by AV.

The decreased time-cost of travel could also incentivize people to live outside of the city (Litman 8). In addition to being able to utilize their travel time, it is generally cheaper to live outside of the city. These people will have a longer commute to work, increasing total VMT.

Many MPOs have attempted to model the effect of AVs on VMT (Guerra 216). It is worth noting that the models Guerra discusses "… clearly stretch current model capabilities, and depend on highly uncertain inputs." (Childress et al.[4]). With that said, the majority of the models he analyzed predicted a 5 to 20 percent increase in VMT (Guerra 217).

Increased VMT could pose a risk to the environment via increased pollution. However, this may not be significant if AVs are electric as opposed to gas or diesel fueled. This is likely for several reasons. First, consumers will want electric AVs; although electric vehicles generally cost more up-front, they are cheaper to maintain in the long run (McCauley, par. 12). Second, manufacturers will prefer to develop electric AVs, as they are easier for an AV to operate (McCauley, par. 6).

Finally, AVs will make it possible for non-drivers to travel in a car by themselves. Non-drivers include children under age 16, the elderly, and people with various disabilities (blindness, deafness, mental, etc.) Ignoring for now the effect on congestion, this is a very positive effect. For children, it will likely save their parents' time that would've been consumed driving their children everywhere they need to go. AVs will allow the elderly and disabled to perform necessary errands, such as grocery shopping and doctor visits, as well as reducing social isolation (Anderson et al. 36).

However, in terms of congestion, this effect is very difficult to quantify and estimate. As these groups of people generally need assistance beyond just driving (eg. entering and exiting the vehicle), it is difficult to predict how feasible it will be for them to travel alone. Also, these groups of people could face difficulty if the AV breaks down, or if they need personal assistance

[4] As cited in (Guerra 217)

during transportation. Also, if they use the system incorrectly, they may end up going somewhere they didn't intend to, or travel through a dangerous area, endangering themselves and the vehicle. Thus it seems likely that, even though an AV passenger won't need to hold a driver's license, they should have to demonstrate that they understand how to operate the AV's controls. Therefore, the number of current non-drivers that will be able to ride alone in an AV will likely be small.

Comparative Analysis

AVs have the potential to resolve several of the problems which induce recurring congestion, as identified by the 2012 TTI Urban Mobility Report. V2V communication will allow AVs to utilize established roadways more efficiently than human-operators can. Since AVs will allow for more narrow lanes, more lanes can be added without using more space. Also, rerouting using V2V communication will change usage patterns in real time and reduce congestion during peak hours. Finally, traffic flow will be improved, as AVs won't brake or accelerate as sharply as human-operators do. Additionally, AVs will be able to reduce some forms of non-recurring congestion. Once AVs don't have to share the road with humans, traffic incidents will be largely eliminated.

Empty vehicle traffic is unlikely to have a significant effect on congestion, as it will not introduce a substantial amount of new vehicle traffic onto roads. The influx of new traffic generated by the increased mobility of non-drivers is not likely to be an imminent effect, as it seems infeasible that these people will travel alone until people are very comfortable with AVs.

The most noteworthy drawback of AVs on congestion is their likely increase of VMT. The overall effect of AVs on congestion is likely dependent on the ability of the increased efficiency of AVs to counteract the increased VMT. It seems likely that this will be possible.

Considering VMT and roadway throughput alone, Guerra stated that a 5 to 20 percent increase in VMT was likely, while Shladover et al. expected that roadway throughput will nearly double under AVs (Guerra 217; Shladover, Su and Lu 11). Considering that there are many more ways that AVs will decrease congestion beyond increased throughput, it seems likely that AVs will generate a net decrease of congestion.

Conclusion

Autonomous vehicles will reshape the city even more profoundly than the automobile reshaped the Walking City and Streetcar City. They will necessitate the redesign of roadways, and will impact nearly every aspect of how we travel on roads, whether by car, bicycle, or by foot.

In some ways, AVs will exacerbate the effects that automobiles originally had on the city. For instance, the trend of suburbanization is likely to continue and increase as AVs lower the time-cost of travel. In other ways, AVs have the potential to undo some of the adverse changes that automobiles forced on cities. While automobiles have dominated land use in cities, AVs will require much less space, which can be given back to pedestrians.

As with the human-operated automobile, the overall impact of AVs on the city will be neither wholly good nor wholly bad. However, based on historical evidence, projected statistics, and case studies developed by experts in urban studies, it is likely that autonomous vehicles will decrease roadway congestion.

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