Highway Capacity Impacts of Autonomous Vehicles: An Assessment

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1. Introduction

Autonomous vehicles have received much attention in the recent past. Many view AVs as much closer to reality than they have been perceived to be. New car models available in the market already include a variety of semi-autonomous features such as adaptive cruise control (ACC), self-parking, lane guidance, and collision avoidance. Technology giants and automobile manufacturers are working toward complete automation, also called level-4 automation, where "*The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. ... This includes both [human] occupied and unoccupied vehicles.*"[1] Google reports over 500,000 miles of testing AVs on public highways, while several auto manufacturers have announced the release of AVs within the next 5 years.[2]

There is also considerable discussion and speculation on the influence that AVs can have on the way we travel and on our transportation systems. Some believe that the AVs can potentially transform our lives and transportation systems in the near future[3], while others provide a cautiously optimistic picture and present a long way ahead (several decades) before the many benefits of AVs can be fully realized[4]. The potential benefits of AVs include, but not limited to: (1) independent mobility for elderly, disabled, and other mobility-constrained population segments, (2) better use of travelers' travel time for productive work or leisure, (3) increased highway safety due to the elimination of human error in driving; assuming that AVs will not be subject to system failures and abuse, (4) reduction in fuel consumption and emissions due to smoother acceleration/ deceleration characteristics and improved traffic flow characteristics, (5) increased road capacity and reduced congestion.

The goal of this white paper is to provide a review and discussion on the role of AVs in enhancing roadway capacity and reducing traffic congestion. In doing so, the paper reviews the influence of AV technologies on traffic flow behavior and resulting highway capacity improvements (Section 2). While the AV technology can lead to significant improvements in traffic flow behavior, penetration of AVs into the personal automobile markets can induce additional travel with additional capacity needs. Therefore, the paper presents a discussion of the influence of AVs on our lifestyles in general and travel behavior in particular for assessing the potential of AVs in inducing additional travel (Section 3). The extent of any of the above discussed benefits of AVs will depend on the market penetration of AVs. Therefore, a section is devoted to the issue of AV market penetration (Section 4). The paper concludes with a discussion and recommendations toward an implementation framework for AVs (Section 5).

2. Implications to Traffic Operations and Highway Capacity

A widely cited benefit of AVs is a safer, smoother, and more efficient operation of urban traffic systems than with today's human-driven cars. Assuming no systemic failures and no malevolent human tinkering, AVs have the potential to eliminate human error in driving which is known to be a predominant (>90%)[5] cause of traffic crashes. The reduction of traffic crashes and consequent secondary incidents will alone lead to significant efficiencies in traffic operations by reducing non-recurrent congestion, because 25% of traffic congestion can be attributed to traffic incidents such as crashes and vehicle breakdowns[6]. While AVs alone may not lead us to zero-crashes (and they might bring in other risks due to system failures and intentional abuse), there is a general consensus among both advocates and critics of AVs that the number of crashes is likely to decrease. Besides, considering that there were more than 5 Million police-reported traffic crashes in the United States in 2011[7], even halving these crashes will lead to significant reduction in traffic congestion. When the technology is fully mature and the market penetration of AVs is at saturation, some believe that there is a potential to bring down the traffic crash rates at par to those in aviation. Of course, all of this is assuming that the AV technology is fully mature and that the technology doesn't bring in new risks. While today's AVs have been demonstrated to drive safely in many typical driving situations (especially in freeways), a fully autonomous system that can perform safely in any (and every) situation may not be practically feasible.[89] Poor weather (fog, snow, and rain) is a known challenge to today's AV sensor technology and driving performance. Likewise there may be many other known and unknown situations for which the technology is yet to evolve.

A typical highway with all human-driven vehicles provides a maximum throughput of about 2,200 vehicles per hour per lane, which is also called the roadway capacity. This reflects only 5% utilization of the roadway space. On the other hand, AVs can allow a much better utilization of roadway space. This is because AVs can better sense and anticipate the lead vehicle's braking actions and acceleration/deceleration decisions than human drivers. The technology allows much smaller perception and reaction times (than that needed for humans), smoother braking, and shortening of vehicle-following gaps even at high speeds. Further, unlike human-driven vehicles, the speed and traffic flow performance of AVs does not degrade in narrow lanes due to more accurate steering. It is well-known that humans tend to drive at much slower speeds in lanes narrower than 12 ft width. Besides, AV technologies allow a smoother flow of traffic by smoothing out traffic destabilizing shock waves and better platooning of vehicles (i.e., traveling in groups with smaller speed variance).

At high market penetration, the AV technology can potentially make it possible to move toward an advanced form of vehicle platooning where convoys of vehicles move at high speeds and small spacing in between. This approach is being tested in the trucking industry where a number of driverless trucks are coupled together and lead by a human-driven truck. While the majority of large truck flows are on freeways, the AV technologies are beneficial in the urban environments as well, toward reducing the spacing between trucks and passenger vehicles. In today's highway capacity analysis, each truck is considered equivalent to about 2.5 cars in terms of roadway capacity consumption, partly because of the large spacing needed between human-driven trucks and human-driven passenger cars. The AV technology can significantly help in reducing the inter-vehicle spacing even in the presence of trucks.

AV technology can help improve traffic flow not only through uninterrupted traffic flow facilities such as freeways and arterials, but also through interrupted flow facilities such as highway intersections. First and foremost, as the AV technology evolves to avoid traffic collisions at intersections, significant benefits are in hold not only from a safety perspective but also for a better traffic flow through intersections. In addition, the AV technology allows shorter headways/spacing between vehicles and smaller startup lost times at signalized intersections and a smoother stop-and-go movement through intersections without traffic signals. A sizeable proportion of traffic signals in urban areas are pre-timed for peak hour traffic flow patterns. Such peak-hour related signal timing designs may not be optimal for off-peak hours of the day. While automated actuation of traffic signals is a well-known and widely used practice, as the AV technology evolves, it is possible to better automate signal timing designs and adopt more intelligent intersection management practices. All these developments can lead to significant reductions in intersection delay and therefore notable increases in highway capacity within urban regions. In combination with other technologies such as the ubiquitously available mobile internet, v2v and v2i technologies, the AV technology can potentially help usher in new era of real time and dynamic traffic management. It is possible to track vehicular traffic (barring privacy concerns) and predict spatial and temporal patterns of congestion that can be addressed in a timely manner.

Complete penetration of fully autonomous vehicles (i.e., level-4 autonomy, where the human driver is not needed for the entire trip) into the traffic mix, even if possible, is at least a few decades away. Therefore it is best to discuss the above discussed benefits in the presence of mixed traffic (with a mix of human driven vehicles and autonomous vehicles) and with different extents of automation. Of course, many of the above discussed benefits may not be fully realized until high AV shares are present. At low penetration rates, such as a 1% of all vehicles on a highway segment are AVs, the highway capacity and congestion reduction benefits will likely be none to very little, except that the presence of AVs in the traffic, even if sporadically, may influence other travelers' decisions to purchase AVs in the future. It is also likely that in early stages with low presence of AVs in the traffic streams, other drivers might prefer greater than normal spacing from the AVs (due to potential safety related perceptions). As the penetration of AVs increases, the highway capacity and congestion reduction benefits will start kicking in, of course at higher penetration rates. Besides, as the AV penetration increases, it is possible to start dedicating lanes to AVs for greater traffic flow benefits.

Several studies have investigated the benefits of partial automation features available in today's vehicles. For instance, semiautonomous vehicles equipped with adaptive cruise control (ACC) systems can automatically adjust speed for maintaining a set spacing from the lead vehicle. Bose and Ionnu[10] use simulations to demonstrate that 10% semiautonomous vehicles in the traffic mix (with mixed traffic) can help smooth the traffic from rapid accelerations of human-driven vehicles. They estimate significant savings in fuel consumption (28%) and reductions in air pollution due to rapid acceleration, without significantly reducing the traffic flow rates. However, it is not clear if these traffic smoothing benefits leads to considerable improvements in highway capacity in traffic deceleration situations (e.g., in stop-and-go traffic at congested conditions).

Research shows that the capacity benefits can be realized to a greater extent when the AV technology is combined with connected vehicle technologies such as vehicle-to-vehicle (v2v) and vehicle-to-infrastructure (v2i) communications. For instance, Shladover et al.[11] estimate that human-driven vehicles equipped with the adaptive cruise control (ACC) feature leads to very modest increases in the highway capacity, if the drivers choose the spacing between vehicles. On the other hand, use of the cooperative adaptive cruise control (CACC) technology, which allows communications between vehicles, can significantly increase highway capacity at moderate to high market penetration (at 100% presence of CACC vehicles in the traffic mix). However, at small market penetration rates such as 10% even CACC technology does not lead to discernible capacity benefits. At 50% market penetration, they estimate a maximum capacity of 2685 vehicles per hour per lane (vphpl), which is 22% higher than the today's typical highway capacity (of 2200 vphpl). At 80% and 100% penetration rates, they estimate a maximum capacity increase of 50% and 80%, respectively. The authors find that, even if not all vehicles are CACC equipped, a mix of CACC vehicles and other vehicles with short-range communication radios can help in increasing highway capacity. In another study, Tientrakool et al.[12] estimate that, at 100% presence in the traffic mix, vehicles equipped with automatic braking capability and partial automation features (such as sensors of lead vehicle speed) can increase highway capacity up to 40%. For vehicles equipped with automatic braking, sensors, and v2v communication, they estimate that even a 50% presence in the traffic mix can increase the highway capacity by 80%. They suggest a linear increase of capacity benefits with increase in the presence of individual vehicle automation features (such as speed sensors on the vehicles). On the other hand, increase of v2v communication helps in achieving a non-linear increase in the capacity benefits with increase in the percentage of communicating vehicles. The former study (by Shladover et al.) assumes human intervention for braking while the latter study (by Tientrakool et al) considers automatic braking capability. Clearly, the AV technology can bring significant synergy to the v2v and v2i technologies and vice versa. Besides, results from the above studies suggest the need for at least a moderate extent of AV market penetration needed for discernible highway capacity benefits. High market shares are needed for significant capacity benefits.

Some discussion is in order here on traffic analysis in the presence of AVs. As the penetration of AVs increases, the traditional approach to highway capacity modeling and level-of-service assessment will need to evolve. Traffic flow analysis will need to incorporate car following models that consider realistic patterns of car following in the presence of AVs. The assumptions of vehicle acceleration/deceleration and braking behaviors in these models might vary by the extent of the presence of AVs (and the extent of automation) and human-driven vehicles in the traffic mix. Intersection traffic signal timing algorithms will need to consider alternate assumptions of startup lost time and vehicle following behavior at the intersections. The current definition of highway level-of-service (LOS) is based on traffic density, where closer spacing between vehicles is designated a poor LOS rating. As AVs penetrate at higher levels into the traffic mix either the density thresholds used for designating different LOS ratings may have to be changed or the entire concept of density-based LOS rating should be revised. Clearly, more research and experience (with more AVs on the roadways) is needed to gain a better understanding of the revisions needed for highway capacity modeling practice in the presence of AVs.

Finally, it is worth noting that while the AV technology can potentially improve traffic flow patterns and highway capacity, penetration of AVs into the personal automobile market can potentially induce additional travel due to the influence they have on our lifestyles in general and travel behavior in particular. To the extent that additional travel is induced, the capacity benefits due to AVs will be offset by the additional travel. The next section provides a discussion of the influence of AVs on lifestyles, travel behavior, and the resulting additional travel induced.

3. Influence on Lifestyle and Travel Behavior

AVs can potentially bring about significant changes in the lifestyle of those who own and use them, particularly at high rates of market penetration of AVs. The lifestyle choices relevant to urban transportation include: (1) individuals' long-term, land-use related choices such as residential location choices and automobile ownership, and (2) travel behavior choices such as why, how, how much, where, and when we travel. The AVs will not only influence individuals' life style choices, but also influence how businesses are conducted, which will in turn have an influence on our travel behavior. This section provides a qualitative discussion of these impacts as the currently available evidence is limited to quantify the impacts. The impacts will be discussed in the context of two distinct scenarios: (1) when the AVs penetrate the personal automobile market considerably, and (2) when the AVs are used more as a transportation service in the form of car sharing and taxi services, as opposed to being personal vehicles.

3.1 Land-use Related Choices

One of the benefits of AVs, when there is no need of a human driver, is that the time in the vehicle will less likely be wasted "behind the wheel". To the extent that AVs become fully autonomous without the need of a human instruction from the beginning to the end of the trip, passengers can utilize the travel time in the vehicle for productive work, leisure, and other activities as opposed to driving the vehicle and watching for potential hazards. Then people might not hesitate to reside farther away from work locations, since they do not have to "drive" to work; the commute time can be used in many ways. This trend can fundamentally influence our land-use patterns toward more sprawled cities, leading to greater distances traveled and higher VMT than today.[13] Of course, there might be other opposing forces toward more compact cities, such as "freeing up"[1] of parking spaces in the urban centers and increasing preference for compact and socially vibrant neighborhoods. However, depending on land-use policy and the extent of AV penetration into the personal vehicles market, sprawl may still continue to happen.

A related influence of AVs is the location choices of businesses or employers. Businesses that are currently locating in central locations for better accessibility to clients and employees will want to move out to less expensive locations farther from the city centers. As travel time becomes productive or useful, the influence of longer travel times on employees' location choices decreases. Therefore, businesses will want to reduce their location-expenses by moving away to remote locations. This will further lead to increases in VMT with implications to additional roadway capacity needs.

Sprawled cities will certainly lead to higher VMT if AVs penetrate a significant share of the personal automobile market. On the other hand, as will be discussed later, there is scope for much efficient travel and use of cars if AVs are used as a transportation service in the form of car sharing or taxi services.

3.2 Vehicle Ownership Choices and Preferences

At higher penetration rates of AVs into the personal automobile market, as automakers and technology companies make it more affordable to own these cars, the household AV ownership level might increase significantly. Currently, the average car ownership level is about one vehicle per licensed driver in the household. With AVs, depending on the legislation, the personal vehicle ownership could reach up to one vehicle per person, including children. If individuals do not need a license to travel in these vehicles and if children are also allowed to travel independently, it is not inconceivable that those who can afford might want to have one

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[1] Another land-use related influence of AVs is potential de-coupling[1] of parking land-uses from the buildings in which human activities are conducted. Currently, parking spaces (and lots and garages) are adjacent to most buildings. Since the AVs can potentially drop passengers at the activity location, park themselves at another location, and pick up the passengers when needed, the need for on-site parking can reduce considerably.

vehicle per each child (say, school going children) in the household as well. This will help avoid the need for parents chauffeuring their children to school. Of course, the extent of this trend depends on the affordability of AVs and the legislation on whether school-going children can travel alone in these vehicles. The rate of car ownership among elderly can be expected to rise considerably. The increases in car ownership rates will undoubtedly lead to increases in VMT, which will in turn have an offsetting influence on the roadway capacity utilization and congestion reduction due to AVs.

Another dimension of automobile ownership is vehicle type choice. In the context of AVs, there will likely be a preference toward larger vehicles as individuals can conduct activities other than simply being seated. Additional space needs for equipment such as televisions and computers might increase. To add to this, the electronics industry will grab the market opportunity to equip AV compartments with gadgets and devices for a better travel experience. As the AVs enter the mass production phase and penetrate the automobile market considerably, it is not inconceivable that those who drive longer distances might prefer vehicles closer to the size of recreational vehicles with all facilities inside, unless legislation and other policy restrictions intervene.[14] The shift toward larger sized vehicles will have implications to roadway capacity consumption, parking consumption, roadway widths in residential neighborhoods, and fuel consumption. The need for larger vehicles will in turn increase the need for larger housing lots (for parking and wider streets) and therefore farther residential locations and greater sprawl.

3.3 The Rise of Alternatives to Personal Vehicle Ownership

The above discussion considers only the scenario when AVs penetrate the personal vehicle market. However, some[15] argue that with increasing presence of car-sharing systems and other alternatives to personal vehicle ownership, there will be a much decreased need for individuals and households to own cars personally. Even without automation, studies have shown that car sharing services tend to reduce personal automobile ownership.[16] With the penetration of AVs into the market, it is very much conceivable that alternatives to personal vehicle ownership may rise. For example, individuals who currently own cars out of necessity than preference will likely switch to car-sharing if the service is available at a comparable or lower expense than owning personal automobiles.

A variety of factors will influence how the automobile ownership and usage model will evolve – toward a personal vehicle fleet, a shared vehicle fleet used as a car sharing or taxi service, or some combination of personal vehicles and shared vehicles. Some consumers may not want to part from the ability to drive and control a vehicle, and some others may want to own driver-less cars as opposed to share them. Besides, car manufacturers have historically projected the automobile as a way of better lifestyle than simply as a means for travel between point A and point B. Aggressive marketing campaigns to promote personal ownership of AVs will likely continue. At the same time, there has been a decreasing affinity to own and/or drive cars particularly among the millennial generation and also among other age groups. Besides, car-sharing services are gaining popularity and market presence in many cities in the US[17] and around the world. Furthermore, personal automobiles involve large outlays of capital expenditure, whereas expenditures on car-sharing and other services depend on the extent of travel. To avoid high ownership costs, people might choose not to own AVs and utilize the service of AV-sharing systems where they pay by usage. Burns et al.[18] estimate, in a case study for Ann Arbor (MI), that a shared autonomous vehicle fleet can reduce per mile travel costs by 75% (i.e., from 59 to 15 cents per mile) when compared to personally owned vehicles driven 15,000 miles per year. Besides, if AVs penetrate into and increase the extent of car-sharing services, a much smaller size of vehicle fleet would be needed to serve our travel needs than the number of personal automobiles owned today. In a case study for an upcoming small town called Babcock Ranch in Florida, Burns et al. estimate that a shared autonomous vehicle fleet size of less than 4000 would be sufficient to serve the within city peak-period travel of over 50,000 population, while keeping the average wait time of travelers well under a minute. Preliminary results from another study by Fagnant and Kockelman[19] suggest that a single shared AV could potentially replace about eleven household-owned vehicles. Just as important, AVs can make it easier to use car-sharing services, because the user does not have to travel to and from the location of the car; the car will self-drive to pick-up and drop-off the user at any location. Finally, and very importantly, legislation will play a significant role in determining the ownership/usage model of AVs.

It is worth noting that alternatives to car ownership include not only car sharing services, but also taxi services, car rental services, and ride sharing services. All these forms of forms of demand response services share similarities as well as have their own distinguishing features. In addition, in combination with other technologies such as the ubiquitously available mobile internet, innovative forms of vehicle sharing may emerge. For example, it is possible that people might personally own AVs, use them for their own travel as well as allow the vehicles to be shared by others when they are not using the vehicles (perhaps as a profit making venture through a car-sharing service).[20]

3.4 Travel Behavior Impacts

AVs can influence our travel behaviors in many different ways. This section provides a discussion of these influences under two different scenarios: (1) when the AVs penetrate the personal automobile market considerably, and (2) when the AVs are used more as a transportation service in the form of car sharing and taxi services, as opposed to being personal vehicles.

3.4.1 Scenario 1: AVs Penetrate the Personal Vehicle Market

In the scenario when AVs penetrate the personal vehicle market considerably, the above discussed lifestyle changes due to AVs will directly influence the way we travel. The travel distances will potentially increase as one can utilize the travelling time for work and other activities as opposed to non-productive driving time. As the cities sprawl, the vehicle miles traveled (VMT) will increase significantly. Besides, it may become difficult to draw those who can afford personal AVs to other modes of travel such as public transit (if it exists in the current form). This implies higher auto mode shares.

There is a good chance AVs will be used for “door-to-door” travel, without the need for humans parking the vehicles; at full maturity of the AV technology the vehicles can pick-up (drop-off) passengers right at the origin (destination) and self-park at a remote location. The implication is that there will be several “empty” AV trips without a passenger (i.e., zero-occupant travel). All these are new trips that do not exist today. Assuming a rather conservative estimate of 1 mile of empty travel per a 10 mile trip, the VMT will increase by 10% simply because of empty travel. Another scenario of significant zero-occupant travel is when personal AVs are used to drop-off a passenger at one location and pickup another passenger from another location and so on. For example, households that can afford to own fewer vehicles than needed may use their vehicles for drop-off one household member at a desired location, travel back home to pick-up the other member and so on. This will likely generate significant zero-occupant travel between the different locations. Besides, the amount of VMT by non-working household members can increase significantly compared to the current scenario.

Some zero-occupant travel may happen for useful trips, such as shopping where AVs are sent to shop (assuming that drive-in type of services will evolve where shopping can be completed without the presence of a human being). While this helps reduce the personal travel time, it can potentially decrease the efficiency in shopping, where the tendency to shop as needed may increase as opposed to shopping for creating an inventory of groceries at home. Similarly, several other activities, especially maintenance activities that do not necessarily need the human being (sending clothes to laundry, pick-up of goods purchased online from within a close proximity) may be carried out using zero-occupant vehicles. This trend can reduce the efficiency mechanisms many people incorporate in their daily travel patterns through trip-chaining where trips to grocery shopping and other non-work activities are combined with commute travel. The result is an increase in VMT.

Over the next two decades nearly one fifth of the population will be over the age of 65. While the typical trend has been that individuals reduce traveling, give up driving, or cannot drive with increasing age, the AVs have the potential to provide mobility for most elderly people. This is a significant benefit to the society. From a roadway capacity standpoint, the extra travel by all the elderly might add additional vehicle miles traveled (VMT) on the roadways. Similarly, children traveling alone in vehicles can potentially increase VMT significantly.

The other form of AVs' influence on travel is through their impact on businesses. The AV technology, combined with mobile phone internet and other technologies, will have a far-reaching influence on the way several businesses are conducted. First, as discussed before, employers will have an incentive to move to remote locations, which will increase the miles traveled to work and for business. Besides, the AVs will provide numerous opportunities for wide range of businesses, both existing and new businesses. For example, several retail businesses will evolve into a drive-in service model, where the consumer products are simply dropped into unmanned AVs. For instance groceries may be purchased online while an unmanned AV can pick up the groceries from the store. Likewise, urban delivery services (say, pizza delivery) will start using unmanned AVs for cutting down the costs of human drivers. To take this a step further, transport of freight goods over longer distances may not need as many human drivers as it needs now, which will have a disruptive influence on the trucking industry. Use of AVs for freight transportation can significantly reduce travel times for long hauls (as AVs do not need long rest hours as human drivers do). This can in turn change the logistics decisions (and related freight transport decisions) of several industries in many different ways.

3.4.2 Scenario 2: AVs Boost the Shared Vehicle Market

The above discussion does not consider the scenario when AVs are used more as a shared vehicle service than personal vehicles. As discussed before, AVs and with other technologies provide a significant opportunity to promote the use of automobiles as shared vehicles as opposed to personal vehicles. Conscious efforts of policy makers, transportation planners, and other stakeholders, combined with an increased sustainability consciousness among the public, can lead us into a future where the car ownership model might transform into a shared autonomous vehicle fleet model. Research on the users of existing car sharing systems provides empirical evidence that those who use these systems tend to travel less than those who own automobiles.[21] Analogously, one can expect higher efficiency in the way people travel using shared AVs when compared to the anticipated travel demand patterns with personally owned AVs. But when compared to the current scenario of personally owned human driven vehicles, even shared AVs can induce significant additional travel (e.g., travel by elderly and young children). Recent studies suggest that shared AV fleets can rival the traditional personally owned automobiles in providing mobility while also reducing congestion and environmental impacts and being safer and more economically viable (see Kornhauser et al.[22] and Brownell[23], also see Fagnant and Kockelman[24]). However, it is perhaps a bit too early to make conclusive statements on whether congestion reductions due to better traffic flow characteristics of AVs and the efficiencies due to shared vehicle systems are sufficient to offset the additional capacity needs due to AVs. While shared AV fleets minimize certain forms of additional travel such as empty trips, other forms of AV-induced travel such as travel by older adults and younger children and longer travel distances may still be on the higher side.

Shared AV fleets can potentially limit the extent of urban sprawl as well, when compared to the case with only personally owned AVs. This is because the shared vehicle fleet model works more effectively for smaller service areas by reducing the number of empty miles and enabling a more efficient usage of the fleet. However, when compared to the current scenario of human driven vehicles, a combination of shared AV fleets and personally owned AVs will likely lead to more sprawled cities.

In short, the move toward shared AV fleets appears to be a promising future with better mobility at lower costs while also reducing negative externalities such as traffic crashes. But it is not clear, if the capacity improvement benefits outweigh the additional capacity needs due to AV-induced travel. Clearly, the future with AVs holds significant uncertainty. Of course, the possibility of different AV futures depends on the extent of market penetration of AVs and the form in which they are predominantly used, a source of great uncertainty.

4. Market Penetration of Autonomous Vehicles

Market penetration and consumer adoption is an important yet one of the most uncertain issues related to AVs. Technology companies[25] and automobile manufacturers[26] have announced aggressive timelines for the release of these vehicles. Thanks to DARPA’s (Defense Advanced Research Projects Agency) urban challenge projects, Google, and auto manufactures’ efforts, there have been significant technological advances in the recent past. Google has demonstrated over 500,000 miles of driver less car travel in real conditions. After such disruptive jolts, technology is likely to advance rapidly. Yet, achieving self driving systems that can safely navigate in any (and every) situation is a challenge. For example, the technology is yet to evolve for safe navigation of AVs in adverse weather conditions. However, both enthusiasts and skeptics of AVs believe that technology is less likely to be a barrier (see a debate on this issue by The Economist). Many believe that the availability of AVs is more a question of “when” than “if”. Expert members of the Institute of Electrical and Electronics Engineers (IEEE) view AVs as one of the most promising forms of intelligent transportation systems.

While there is much belief and hope that the AV technology will evolve rapidly, many believe that economic, social, and legal/political aspects can slow down the market penetration. In this context, Chunka and Carrooll state that "*technology improves exponentially while social, political, and economic systems tend to change incrementally*."[27] Barriers to rapid penetration of AVs into the market include high costs of the technology[28], consumers' continued preference to drive and "control" a vehicle, lack of a legal framework for AVs, liability issues (who is responsible if a crash happens?), licensing issues, privacy concerns regarding data sharing, and security issues due to system failures and intentional abuse or attacks. While some of these issues such as costs may be viewed as relatively easy (i.e., costs can be expected to go down over time in a competitive market), complex litigation/liability issues will need concentrated efforts. System security issues, although not common, pose a significant threat; a single event may set back the overall progress in significant ways. Most important, AV-related legislation needs to be in place for the availability of AVs for mass consumption. Given all these issues, it is likely that the market penetration of AVs will not be immediate but will happen in a gradual fashion, albeit at an accelerated rate.

The current forecasts of AV market penetration vary considerably. In this context, Yoshida[29] notes the following: *"It turns out that opinions and forecasts among industry experts wildly vary -- ranging from an estimate of 20-30 million to 95 million autonomous cars around 2030 to 2035.* Expert members of IEEE estimate that 75% of all the vehicles will be autonomous by 2040.[30] A market research firm expects autonomous cars that are highly automated (but not fully self-driving) to have a market share of around 15 to 20 percent globally by 2030. According to them, fully autonomous cars will be in the low single-figure percentages.[31] Another market report[32] forecasts that "*autonomous vehicles will gradually gain traction in the market over the coming two decades and by 2035, sales of autonomous vehicles will reach 95.4 million annually, representing 75% of all light-duty vehicle sales.*" Todd Littman[33], based on an analogy with the evolution and market penetration of previous automobile technologies (e.g., air bags) and other technologies, forecasts that a major share of vehicles (and travel) may be autonomous only in 2040s through 2060s, yet with a mix of human driven vehicles. While these different forecasts are not easy to compare, the latest years with most optimistic predictions in the above mentioned forecasts is 2030-2035, suggesting that a significant penetration of fully autonomous vehicles into the traffic mix is at least a couple of decades away.

5. Summary and Recommendations for an Implementation Framework

There has been much excitement and speculation about Autonomous vehicles (AVs) recently. At high maturity of the technology and considerable penetration into the automobile market, significant benefits are in hold, including enhanced highway safety, the availability of travelers' travel times for productive work or leisure, independent mobility for elderly, children and disabled, notable improvements in traffic flow patterns, and the potential for reductions in congestion, fuel consumption, and emissions. At the same time, there will likely be significant induced or additional travel leading to increased fuel consumption and capacity needs to offset the benefits associated with congestion reduction and environmental impacts. It is probably a bit too early to conclude whether the traffic flow improvements outweigh additional induced travel. Nevertheless, many experts speculate that the overall benefits outweigh potential negative externalities. Besides, the technology has the potential to cause a disruptive change in the way we live, conduct business, and travel. The land-use patterns, car ownership model, and travel demand patterns can change significantly altering the nature of transportation systems.

Many of the above discussed benefits of AVs are likely to be realized at high penetration of these vehicles into the traffic mix. Recent technology advances and the interest of technology companies and car manufacturers in making these vehicles suggest a promising outlook for the availability of these vehicles in the near future. Many believe that the availability of AVs in the market is more a question of "when" than "if". While AVs may be available commercially in the next 5 years (as promised by technology giants and car manufacturers), mass penetration of AVs at high proportions into the market is at least a few decades away. This is due to the time needed for reduction in the costs to make it affordable for most income groups, the need for a legal framework for AVs, liability related complications, privacy concerns and potential security issues. Further the benefits of AVs are likely to be higher in conjunction with other technologies such as v2v and v2i communications that will need significant public infrastructure investment and several years.

Clearly, significant challenges lie ahead for policy makers, transportation planners, and other stakeholders. At the same time, a significant opportunity exists for positioning our transportation systems for maximizing the benefits of AV technologies and for mitigating potential negative impacts. The regions that get to implement AVs in the beginning will have many early starter benefits (e.g., new industry and employment opportunities) in addition to earlier-stated benefits such as independent mobility for elderly. Several recommendations are provided next toward a better facilitation of AV implementation, predominantly geared toward metropolitan regions such as the Tampa Bay Region.

First and foremost, taking advantage of the current state legislation to test AVs, the Tampa Bay region can proactively encourage testing of AVs. Provision of testing facilities, for example, is one way to attract the technology companies and car manufacturers to test their AVs in the region. This will also help in acquiring experience with AVs in the region and increasing the visibility of AVs for the general public (for better consumer adoption in the later stages).

Large market penetration of fully automated vehicles is at least a few decades away, but semi automation can be encouraged in the short-term, perhaps via special incentives for the sale or use of such vehicles. As a simple example, provision of dedicated parking spaces for self-parking vehicles may encourage the purchase of such vehicles. At higher market penetration, even semi-automated vehicles can provide considerable highway capacity benefits.

At smaller rates of market penetration, realizing capacity benefits (such as reducing congestion) may need dedicated autonomous vehicle lanes. To begin with, it might help to allow AVs in toll lanes at discounted toll pricing and through dedicated lanes through existing toll plazas. This may also facilitate a better testing and accumulation of evidence of AVs on traffic flow behavior. Consideration of AV technologies in infrastructure investments and Intelligent Transportation System (ITS) investments can facilitate the deployment of AVs in the longer term. For example, efforts to enhance the Traffic Management Centers (TMC) toward integration with AVs will likely be beneficial.

As the AVs become available commercially, investing in (or encouraging) car sharing services will likely have significant benefits. The availability of AVs through a car sharing service encourages many people to use them (even if for trying out the technology). Besides, as discussed before, shared AV fleet systems will have significant benefits over personally owned AVs in enhancing highway capacity, reducing congestion, and providing mobility for those who cannot afford high costs of purchasing AVs.

The most important barriers to implementation of AVs are the lack of a legal framework and liability and institutional issues. Metropolitan regions can coordinate with the state governments, insurance companies, and other stakeholders to facilitate the development of a legal framework and to resolve the liability issues. In addition, issues regarding licensing need to be resolved as well (do people need a license to ride AVs? can children be allowed to ride alone?).

Given several forecasts suggest a considerable presence of AVs in about two decades (which is also the time horizon for MPO long-range transportation planning (LRTP) process), it useful to consider the influence of AVs in the log-range transportation planning process. Since the penetration and influence of AVs is associated with significant uncertainty, additional work is necessary to determine how best to consider the role of AVs in the LRTP process. At the same time, the current priorities and project plans for enhancing safety and mitigating congestion and emissions should not be kept pending in anticipation that AVs will solve all our transportation problems.

Additional research is necessary on a number of aspects related to AVs, including the market perceptions, future consumer adoption and market penetration rates; accumulation of empirical data and experience from AV travel; influence on congestion, land-use, auto ownership, travel demand patterns, and emissions and energy impacts. It is important that agencies at different levels, ranging from federal to local, support research to better anticipate the impact of AVs, recognize the associated uncertainty, and plan our transportation systems.

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