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Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations

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ABSTRACT

Autonomous vehicles (AVs) represent a potentially disruptive yet beneficial change to our transportation system. This new technology has the potential to impact vehicle safety, congestion, and travel behavior. All told, major social AV impacts in the form of crash savings, travel time reduction, fuel efficiency and parking benefits are estimated to approach $2000 to per year per AV, and may eventually approach nearly $4000 when comprehensive crash costs are accounted for. Yet barriers to implementation and mass-market penetration remain. Initial costs will likely be unaffordable. Licensing and testing standards in the U.S. are being developed at the state level, rather than nationally, which may lead to inconsistencies across states. Liability details remain undefined, security concerns linger, and without new privacy standards, a default lack of privacy for personal travel may become the norm. The impacts and interactions with other components of the transportation system, as well as implementation details, remain uncertain. To address these concerns, the federal government should expand research in these areas and create a nationally recognized licensing framework for AVs, determining appropriate standards for liability, security, and data privacy.

1. Introduction

Over the past few years the automobile and technology industries have made significant leaps in bringing computerization into what has, for over a century, been exclusively a human function: driving. New car models increasingly include features such as adaptive cruise control and parking assist systems that allow cars to steer themselves into parking spaces. Some companies have pushed the envelope further by creating autonomous vehicles (AVs, also called automated or self-driving vehicles) that can drive themselves on existing roads and can navigate many types of roadways and environmental contexts with almost no direct human input. Assuming that these technologies become successful and available to the mass market, AVs have the potential to dramatically change the transportation network. This paper serves as an introduction to AV technology, its potential impacts, and hurdles for transportation professionals and policymakers.

AVs have the potential to fundamentally alter transportation systems by averting deadly crashes, providing critical mobility to the elderly and disabled, increasing road capacity, saving fuel, and lowering emissions. Complementary trends in shared rides and vehicles may lead us from vehicles as an owned product to an on-demand service. Infrastructure investments and operational improvements, travel choices and parking needs, land use patterns, and trucking and other activities

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may be affected. Additionally, the passenger compartment may be transformed: former drivers may be working on their laptops, eating meals, reading books, watching movies, and/or calling friends – safely.

Yet, the proliferation of autonomous vehicles is far from guaranteed. High costs hamper large-scale production and mass consumer availability (KPMG and CAR, 2012; Economist Technology Quarterly, 2012; Grau, 2012; Hickey, 2012). Complex questions remain relating to legal, liability, privacy, licensing, security, and insurance regulation. While individual U.S. states have been advancing AV legislation through incremental measures (Center for Information and Society, 2012), federal guidance has not yet been issued for either fully, or partially, autonomous vehicles beyond testing purposes on public roads. This being noted, NHTSA has identified research needs that need to be addressed before states should begin AV licensing to the general public, indicating that data to establish proper regulatory frameworks are not yet ready (National Highway Traffic Safety Administration, 2013).

At the September 2012 signing of California's law enabling AV licensure (SB 1298), Google founder Sergey Brin predicted that Americans could experience AVs within five years (O'Brien, 2012). Nissan (Nissan, 2013) Volvo (Carter, 2012) and other manufacturers have announced their intentions to have commercially viable autonomous-driving capabilities by 2020 in multiple vehicle models. Assuming an additional five years for prices to drop to allow for some degree of mass-market penetration, AVs may be available on the mass market by 2022 or 2025, approximately two decades after the DARPA (Defense Advanced Research Projects Agency) Grand Challenge's first successful tests. Policymakers need to begin to address the unprecedented issues that AVs could surface, and could potentially aid the introduction of incremental improvements in the meantime.

1.1. AVs today

In 2004, DARPA's Grand Challenge was launched with the goal of demonstrating AV technical feasibility by navigating a 150-mile route. While the best team completed just over seven miles, one year later five driverless cars successfully navigated the route. In 2007, six teams finished the new Urban Challenge, with AVs required to obey traffic rules, deal with blocked routes, and maneuver around fixed and moving obstacles, together providing realistic, every-day-driving scenarios (Defense Advanced Research Projects Agency, 2012). As of April 2014, Google's self-driving cars have driven over 700,000 miles on California public roads (Anthony, 2014), and numerous manufacturers – including Audi, BMW, Cadillac, Ford, GM, Mercedes-Benz, Nissan, Toyota, Volkswagen, and Volvo – have begun testing driverless systems (Wikipedia, 2013). Semi-autonomous features are now commercially available, including adaptive cruise control (ACC), lane departure warnings, collision avoidance, parking assist systems, and on-board navigation. Europe's CityMobil2 project is currently demonstrating low-speed fully autonomous transit applications in five cities. Additionally, AVs are becoming increasingly common in other sectors including military, mining, and agricultural (Economist Technology Quarterly, 2012). While urban environments pose much greater challenges, these environments can be helpful testing grounds for AV innovation.

States are proceeding with AV-enabling legislation: California, Florida, Nevada, Michigan and Washington, D.C. have enacted bills to regulate AV licensing and operation, with instructions to their respective Department of Motor Vehicles (DMV) for fleshing out details. Yet some of these efforts are in direct conflict with federal guidance. NHTSA (The National Highway and Traffic Safety Administration) has issued a statement advocating that states should begin establishing procedures for allowing testing on public roads, though should not yet begin licensing AV sales to the general public (National Highway Traffic Safety Administration, 2013). In contrast, California has directed its DMV to provide AV certification requirements by 2015 (Center for Information and Society, 2012).

1.2. Paper organization

This paper seeks to explore the feasible aspects of AVs and discuss their potential impacts on the transportation system. This research explores the remaining barriers to well-managed, large-scale AV market penetration and suggests federal-level policy recommendations for an intelligently planned transition, as AVs become a growing share of our transportation system. The paper contains three major sections:

- Potential benefits of autonomous vehicles.
- Barriers to implementation.
- Policy recommendations.

The first section reviews existing literature to ascertain system benefits and impacts with respect to traffic safety, congestion, and travel behaviors. The information is used to estimate and monetize traveler benefits in the form of crash and congestion reduction as well as parking savings across multiple levels of market penetration. The analysis reflects not only autonomous capabilities for individual vehicles, but also increasingly connected and cooperative vehicles and infrastructure systems. The second section investigates barriers to AV adoption and implementation, primarily from a consumer and regulatory standpoint, rather than technical feasibility. These barriers were largely identified in the literature and in discussions with experts. The final section proposes concrete policy recommendations to directly address potential barriers flagged in the second section.

Table 1
U.S. crash motor vehicle scope and selected human and environmental factor involvement.

Total crashes per year in U.S. (Traffic Safety Facts, 2013)	5.5 million
% human cause as primary factor (National Highway Traffic Safety Administration, 2008)	93%
Economic costs of U.S. crashes (Blincoe et al, 2014)	$277 billion
% of U.S. GDP Blincoe et al, 2014; CIA, 2012	2%
Total fatal and injurious crashes per year in U.S. (Traffic Safety Facts, 2013)	2.22 million
Fatal crashes per year in U.S. (National Highway Traffic Safety Administration, 2012)	32,367
% of fatal crashes involving alcohol (National Highway Traffic Safety Administration, 2012)	31%
% involving speeding (National Highway Traffic Safety Administration, 2012)	30%
% involving distracted driver (National Highway Traffic Safety Administration, 2012)	21%
% involving failure to keep in proper lane (National Highway Traffic Safety Administration, 2012)	14%
% involving failure to yield right-of-way (National Highway Traffic Safety Administration, 2012)	11%
% involving wet road surface (National Highway Traffic Safety Administration, 2012)	11%
% involving erratic vehicle operation (National Highway Traffic Safety Administration, 2012)	9%
% involving inexperience or overcorrecting (National Highway Traffic Safety Administration, 2012)	8%
% involving drugs National Highway Traffic Safety Administration, 2012	7%
% involving ice, snow, debris, or other slippery surface (National Highway Traffic Safety Administration, 2012)	3.7%
% involving fatigued or sleeping driver (National Highway Traffic Safety Administration, 2012)	2.5%
% involving other prohibited driver errors (e.g. improper following, driving on shoulder, wrong side of road, improper turn, improper passing, etc.) (National Highway Traffic Safety Administration, 2012)	21%

2. Potential impacts of autonomous vehicles

AV operations are inherently different from human-driven vehicles. AVs can be programmed to not break traffic laws. They do not drink and drive. Their reaction times are quicker and they can be optimized to smooth traffic flows, improve fuel economy, and reduce emissions. They can deliver freight and unlicensed travelers to their destinations. This section examines some of the largest potential benefits that have been identified in existing research. The exact extent of these benefits is not yet known, but this paper attempts to place estimates on these benefits to gauge the magnitude of their impact assuming varying levels of market penetration.

2.1. Safety

Autonomous vehicles have the potential to dramatically reduce crashes. Table 1 highlights the magnitude of automobile crashes in the United States, and indicates sources of driver error that may disappear as vehicles become increasingly automated.

Over 40% of these fatal crashes involve some combination of alcohol, distraction, drug involvement and/or fatigue.[1] Self-driven vehicles would not fall prey to human failings, suggesting the potential for at least a 40% fatal crash-rate reduction, assuming automated malfunctions are minimal and everything else remains constant (such as the levels of long-distance, night-time and poor-weather driving). Such reductions do not reflect crashes due to speeding, aggressive driving, over-compensation, inexperience, slow reaction times, inattention and various other driver shortcomings. Driver error is believed to be the main reason behind over 90% of all crashes (National Highway Traffic Safety Administration, 2008). Even when the critical reason behind a crash is attributed to the vehicle, roadway or environment, additional human factors such as inattention, distraction, or speeding are regularly found to have contributed to the crash occurrence and/or injury severity.

The scope of potential benefits is substantial, both economically and politically. Over 30 thousand persons die each year in the U.S. in automobile collisions (National Highway Traffic Safety Administration, 2012), with 2.2 million crashes resulting in injury (Traffic Safety Facts, 2013). At $277 billion, the annual economic cost of crashes is over double that of congestion (Cambridge Systematics, 2011) and is highlighted as the number-one transportation goal (U.S. House of Representatives and Senate, 2012) in the nation's federal legislation, Moving Ahead for Progress in the 21st Century (MAP-21) (Section 1203§150. b.1). These issues have long been the top priorities of the U.S. Department of Transportation's Strategic Plan. Traffic crashes remain the primary reason for the death of Americans between 15 and 24 years of age (CDC, 2011).

While many driving situations are relatively easy for an autonomous vehicle to handle, designing a system that can perform safely in nearly every situation is challenging (Campbell et al., 2010). For example, recognition of humans and other objects in the roadway is both critical and more difficult for AVs than human drivers (Dalal and Triggs, 2005; Economist Technology Quarterly, 2012; Farhadi et al., 2009). A person in a roadway may be small or large, standing, walking, sitting, lying down, riding a bike, and/or partly obscured – all of which complicate AV sensor recognition. Poor weather, such as fog and snow, and reflective road surfaces from rain and ice create other challenges for sensors and driving operations. Additionally, evasive decisions should depend on whether an object in the vehicle's path is a large cardboard box or a large

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[1] Table 1's factors contributing to fatal crashes are not mutually exclusive. For example, alcohol, drugs, inexperience, speeding, and ice can all contribute to a single crash. As a result, Table 1 percentages sum to more than 100%.

concrete block, and computer vision has much greater difficulty than humans in identifying material composition. When a crash is unavoidable, it is crucial that AVs recognize the objects in their path so they may act accordingly. Liability for these incidents is a major concern and could be a substantial impediment to implementation.

Ultimately, some analysts predict that AVs will overcome many of the obstacles that inhibit them from accurately responding in complex environments. Hayes (Hayes, 2011) suggests that motor-vehicle fatality rates (per person-mile traveled) could eventually approach those seen in aviation and rail, about 1% of current rates; and KPMG and CAR (2012) advocate an end goal of "crash-less cars". However there is the possibility that drivers will take their vehicles out of self-driving mode and take control. Google's only reported AV crash occurred when a human driver was operating the vehicle. The rate at which human control is needed will be a substantial factor in the safety of these vehicles.

2.2. Congestion and traffic operations

Aside from making automobiles safer, researchers are also developing ways for AV technology to reduce congestion and fuel consumption. For example, AVs can sense and possibly anticipate lead vehicles' braking and acceleration decisions. Such technology allows for smoother braking and fine speed adjustments of following vehicles, leading to fuel savings, less brake wear, and reductions in traffic-destabilizing shockwave propagation. AVs are also expected to use existing lanes and intersections more efficiently through shorter gaps between vehicles, coordinated platoons, and more efficient route choices. Many of these features, such as adaptive cruise control (ACC), are already being integrated into automobiles and some of the benefits will be realized before AVs are fully operational.

As the research shows, these benefits will not happen automatically. Many of these congestion-saving improvements depend not only on automated driving capabilities, but also on cooperative abilities through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Vehicle communication is likely to become standard on most vehicles before significant proliferation of AV capabilities throughout the U.S. vehicle fleet, with NHTSA announcing its intention to mandate all new light-duty vehicles to come equipped with V2X capabilities (National Highway Traffic Safety Administration, 2014). Even without V2X communication, significant congestion reduction could occur if the safety benefits alone are realized. FHWA estimates that 25% of congestion is attributable to traffic incidents, around half of which are crashes (Federal Highway Administration, 2005).

Multiple studies have investigated the potential for AVs to reduce congestion under differing scenarios. Under various levels of AV adoption congestion savings due to ACC measures and traffic monitoring systems could smooth traffic flows by seeking to minimize accelerations and braking in freeway traffic. This could increase fuel economy and congested traffic speeds by 23–39% and 8–13%, respectively, for all vehicles in the freeway travel stream, depending on V2V communication and how traffic-smoothing algorithms are implemented (Atiyeh, 2012). If vehicles are enabled to travel closer together, the system's fuel and congestion savings rise further, and some expect a significant increase in highway capacity on existing lanes (Tientrakool, 2011). Shladover et al. estimate that cooperative adaptive cruise control (CACC) deployed at 10%, 50%, and 90% market-penetration levels will increase lanes' effective capacities by around 1%, 21% and 80%, respectively (Shladover et al., 2012). Gap reductions coupled with near-constant velocities produce more reliable travel times – an important factor in trip generation, timing, and routing decisions. Similarly, shorter headways between vehicles at traffic signals (and shorter start-up times) mean that more AVs could more effectively utilize green time at signals, considerably improving intersection capacities.

Over the long term, new paradigms for signal control such as autonomous intersection management could use AVs' powerful capabilities. Some evidence shows that advanced systems could nearly eliminate intersection delay while reducing fuel consumption, though this concept is only theoretical and certainly a long way off. In order to implement such technologies, Dresner and Stone estimate that a 95% or more AV-market penetration may be required, leaving many years before deployment (Dresner and Stone, 2008).

Of course, many such benefits may not be realized until high AV shares are present. For example, if 10% of all vehicles on a given freeway segment are AVs, there will likely be an AV in every lane at regular spacing during congested times, which could smooth traffic for all travelers (Bose and Ioannou, 2003). However, if just one out of two hundred vehicles are AVs, the impact would be non-existent or greatly lessened. Also, if one AV is following another, the following AV can reduce the gap between the two vehicles, increasing effective roadway capacity. This efficiency benefit is also contingent upon higher AV shares. Technical and implementation challenges also loom in order to realize the full potential of high adoption shares, including the implementation of cloud-based systems and city or region-wide coordinated vehicle-routing paradigms and protocols. While AVs have a potential to increase roadway capacity with higher market penetration, the induced demand resulting from more automobile use might require additional capacity needs.

2.3. Travel-behavior impacts

The safety and congestion-reducing impacts of AVs have potential to create significant changes in travel behavior. For example, AVs may provide mobility for those too young to drive, the elderly and the disabled, thus generating new roadway capacity demands. Parking patterns could change as AVs self-park in less-expensive areas. Car- and ride-sharing programs could expand, as AVs serve multiple persons on demand. Most of these ideas point toward more vehicle-miles traveled (VMT) and automobile-oriented development, though perhaps with fewer vehicles and parking spaces. Added VMT may bring other problems related to high automobile use such as increased emissions, greater gasoline consumption and oil dependence, and higher obesity rates.

As of July 2014, state legislation in California, Florida, Michigan, Nevada and Washington, D.C. mandates that all drivers pursuing AV testing on public roadways be licensed and prepared to take over vehicle operation, if required. As AV experience increases, this requirement could be relaxed and AVs may be permitted to legally chauffeur children and persons that otherwise would be unable to safely drive. Such mobility may be increasingly beneficial, as the U.S. population ages, with 40 million Americans presently over the age of 65 and this demographic growing at a 50% faster rate than the nation's overall population (U.S. Census Bureau, 2011). Wood observes that many drivers attempt to cope with such physical limitations through self-regulation, avoiding heavy traffic, unfamiliar roads, night-time driving, and poor weather, while others stop driving altogether (Wood, 2002). AVs could facilitate personal independence and mobility, while enhancing safety, thus further increasing the demand for automobile travel.

Research cites that with increased mobility among the elderly and others, as well as lowered travel effort and congestion delays, the U.S. can expect VMT increases, along with associated congestion, emissions, and crash rates, unless demand-management strategies are thoughtfully implemented (Kockelman and Kalmanje, 2006; Litman, 2013). However, AV benefits could exceed the negative impacts of added VMT. For example, if VMT were to double, a reduction in crash rates per mile-traveled by 90% yields a reduction in the total number of crashes and their associated injuries and traffic delays by 80%. Likewise, unless new travel from AV use is significantly underestimated, research cites that existing infrastructure capacity on roadways should be adequate to accommodate the new/induced demand, thanks to AVs' congestion-mitigating features (like traffic smoothing algorithms (Atiyeh, 2012) and effective capacity-increases (through CACC Shladover et al., 2012), as well as public-infrastructure investments (like V2I communication systems with traffics signals (KPMG and CAR, 2012) designed to support these capabilities. However, other negative impacts, such as sprawl, emissions and health concerns, may not be readily mitigated.

It is possible that already-congested traffic patterns and other roadway infrastructure will be negatively affected, due to increased trip-making. Indeed, Smith argues the possibility that "Highways may carry significantly more vehicles, but average delay during the peak period may not decrease appreciably. Similarly, emissions per vehicle mile traveled may decrease, but total emissions (throughout the day) may actually increase (Smith, 2013)". However, AVs could enable smarter routing in coordination with intelligent infrastructure, quicker reaction times, and closer spacing between vehicles to counteract increased demand. Whether arterial congestion improves or degrades ultimately depends on how much induced VMT is realized, the relative magnitude of AV benefits, and use of demand management strategies, such as road pricing. Emissions have been estimated to fall when travel is smooth, rather than forced, with Berry (Berry, 2010) estimating that a 20% reduction in accelerations and decelerations should lead to 5% reductions in fuel consumption and associated emissions. Thus, while AVs may increase VMT, emissions per mile could be reduced.

Additional fuel savings may accrue through AVs' smart parking decisions (Bullis, 2011; Shoup, 2005), helping avoid "cruising for parking". For example, in-vehicle systems could communicate with parking infrastructure to enable driverless drop-offs and pickups. This same technology could improve and expand car sharing and dynamic ride sharing by allowing for nearby, real-time rentals on a per-minute or per-mile basis. If successful, this offers great promise for program expansions since users could simply order a vehicle online or using mobile devices, much like an on-demand taxi, to take them to their destinations. Preliminary results (Fagnant and Kockelman, 2015) for Austin, Texas using an agent-based model for assigning vehicles around a core region indicate that each shared AV (SAV) could replace around ten privately owned or household-owned vehicles. These simulations assumed that the SAVs operated within a prescribed 12 mile by 24 mile geofence, where trip intensity is relatively high; and longer trips, to or from destinations outside the geofence, were not considered.

As shown in Fig. 1, even in Seattle where vehicle use is more intense than national averages (Puget Sound Regional Council, 2006), just less than 11% of vehicles are "in use" throughout the day, even at peak times, though usage rises to 16% if only including newer vehicles are monitored.

2.4. Freight transportation

Freight transport on and off the road will also be impacted. As one example, mining company Rio Tinto is already using 53 self-driving ore trucks, having driven 2.4 million miles and carrying 200 million tons of materials (Rio Tinto, 2014). The same technologies that apply to autonomous cars can also apply to the trucking industry, increasing fuel economy and lowering the need for truck drivers. While workers would likely still need to load and unload cargo, long-distance journeys may be made without drivers, with warehousing employees handling container contents at either end. Autonomously operated trucks may face significant resistance from labor groups, like the Teamsters, and competing industries, such as the freight railroad industry.

Additional benefits can emerge through higher fuel economies when using tightly coupled road-train platoons, thanks to reduced air resistance of shared slipstreams, not to mention lowered travel times from higher capacity networks (a result of shorter headways and less incident-prone traffic conditions). Bullis (2011) estimates that 4-m inter-truck spacings could reduce fuel consumption by 10–15%, and road-train platoons facilitate adaptive braking, potentially enabling further fuel savings. Kunze et al. (2009) successfully demonstrated a trial run using 10-m headways between multiple trucks on public German motorways, and a variety of autonomously platooned Volvo trucks recently logged approximately 10,000 km along Spanish highways (Newcomb, 2012). However, tight vehicle spacing on roads could cause problems for other motorists

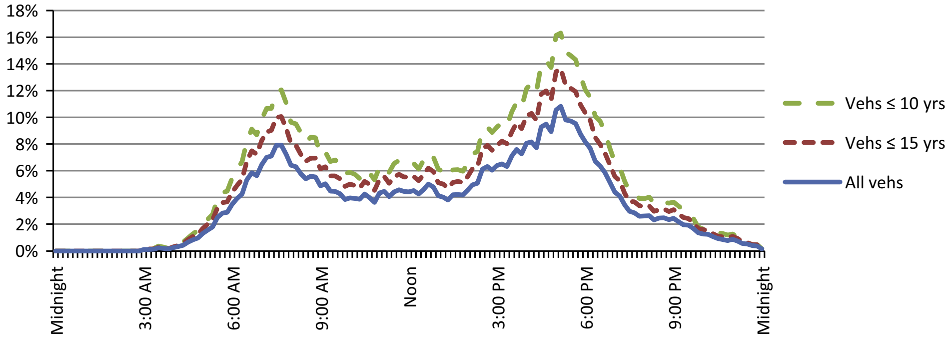

Fig. 1. Vehicle use by time of day and by vehicle age (Puget Sound Regional Council, 2006).

trying to exit or enter highways, possibly resulting in the need for new or modified infrastructure with dedicated platoon lanes and thicker pavements to handle high truck volumes.

2.5. Anticipating AV Impacts

Since AVs are only in the testing phase, it is difficult to precisely anticipate actual outcomes. Nevertheless, it can be useful to roughly estimate likely magnitudes of impact. Based on research estimates for the potential impacts discussed above, this paper quantifies crash, congestion and other impacts for the U.S. transportation system (including changes in parking provision, VMT, and vehicle counts). To understand how AVs' assimilation into the road network might work, multiple assumptions are needed and are explained below. To further understand the impact, the analysis assumes three AV market-penetration shares: 10%, 50% and 90%. These are assumed to represent not only market shares, but technological improvements over time, since it could take many years for the U.S. to see high penetration rates. This analysis is inherently imprecise, it provides an order-of-magnitude estimate of the broad economic and safety impacts this technology may have.

This analysis assumes that primary benefits for AV use will include safety benefits, congestion reduction (comprised of travel time savings and fuel savings), and savings realized from reduced parking demands, particularly in areas with high parking costs. Assumptions that drive these estimated impacts are discussed in this section, as well assumptions that are used to estimate changes in Vehicle Miles Traveled (VMT), to estimate AV technology costs, and to select an appropriate discount rate for net present value (NPV) calculations.

2.6. Changes in VMT and vehicle ownership

VMT per AV is assumed to be 20% higher than that of non-AV vehicles at the 10% market penetration rate, and 10% higher at the 90% market penetration rate. This reflects the notion that early adopters will have more pent-up demand for such vehicles than later buyers. Fagnant and Kockelman's preliminary agent-based simulations (Fagnant and Kockelman, 2015) underscore this idea. For the Austin, Texas market, a fleet of *shared* AVs serving over 56,000 trips a day was found to travel 8.7% of its mileage unoccupied (empty). This figure fell to 4.5% when ride-sharing was permitted, and minor (less than 1%) net VMT reductions were realized when demand rose by a factor of 5 and ride-sharing was permitted. Analysis of the various simulation results suggests that each SAV could serve the same number of trips as 10 household-owned vehicles (if all replaced travel were to lie within the 12 mile × 24 mile geofence). While the 10–1 replacement rate may be too high for mass adoption settings, especially in locations with lots of long-distance trip-making and low-density development, 10 household vehicles are assumed to be replaced here, for every SAV operated (10% of the fleet), resulting in the implicit assumption that around half of all AV trips will be served by SAVs and the other half by personally-owned AVs.

Additional VMT increases may be realized from induced demand, as travel costs and congestion fall. Further, in his review of literature spanning 30 years across California and the U.S., Cervero (2001) showed that the long-term (six years or more) urban area elasticity of VMT (demand for road travel) with respect to the number of highway lane-miles supplied ranges from around 0.47–1.0, averaging 0.74. This suggests that if a region's lane-miles increase by 1%, regional VMT may rise by 0.74% over the long term, after controlling for population, income and other factors. If tolls and/or other traffic management policies are put in place, to stem excessive demand, demand elasticity should be lower. Of course, a 0.74 elasticity value is likely high, since AVs' capacity effects are probably uniform, rather than targeted. Many road segments in a region are not currently congested, and do not exhibit latent or elastic demand. Therefore, if one assumes a 0.37 elasticity, system-wide VMT may be expected to rise 26% under this paper's 90% AV market-penetration assumptions (i.e., the 60% freeway congestion reduction and 15% arterial congestion reduction, due to an increase in effective capacity).

While the congestion-relieving impacts of AVs may be similar to those of adding lane-miles, they differ in another crucial respect, beyond their uniform vs. targeted capacity increases, as noted above. Personal values of travel time (VOTT) may also fall, due to drivers' increased productivity gains which may be freed for purposes other than driving. Gucwa (2014) attempted to estimate the joint implications of increased travel due to capacity and value of travel time changes using simulations of the San Francisco Bay Area. When increasing roadway capacity between 10% and 100%, and simultaneously reducing the VOTT from current levels to somewhere between high quality rail and half of current (in-car) values of time, his model results produced a 4–8% increase in VMT, region-wide, due to changes in destination and mode choices. Of course, AVs may also travel while unoccupied, and long-term housing and employment shifts may also generate extra VMT.

Cervero's (2001) framework (with halved elasticity values) and Gucwa's (2014) simulations produce two different VMT outcomes that may represent the respective high and low ranges of reasonable VMT growth scenarios. Therefore, 20% and 10% increases in VMT per AV were chosen as assumptions for the 10% and 90% AV market penetration rates, respectively, reflecting reasonable estimates within these bounds. These VMT increases are expected to apply system-wide, across personally-owned AVs, SAVs and AVs used for shipping and freight.

2.7. Discount rate and technology costs

For net-present-value calculations, a 10% discount rate was assumed, which is higher than the 7% rate required by the federal Office of Management and Budget (OMB) for federal projects and TIGER grant applications (LaHood, 2011), in order to reflect the greater uncertainty of this emerging technology. Early-introduction costs (perhaps seven years after initial roll-out) at the 10% market penetration level were assumed to add $10,000 to the purchase price of a new vehicle, falling to $3000 by the 90% market-penetration share, consistent with the findings noted in the Vehicle Cost section of this paper. Discussion of internal rates of return for initial costs are also included at the $37,500 level, which may be closer to the added price of AV technologies, a couple years after these are first introduced.

2.8. Safety impacts

U.S. crash rates for non-AVs are assumed constant, based on NHTSA's 2011 values, and the severity distribution of all crashes remains unchanged from present. As noted previously, over 90% of the primary factors behind crashes are due to human errors (National Highway Traffic Safety Administration, 2008), and 40% of fatal crashes involve driver alcohol or drug use, driver distraction and/or fatigue (National Highway Traffic Safety Administration, 2012). Therefore, AVs may be assumed to reduce crash and injury rates by 50%, versus non-AVs at the early, 10% market penetration rate (reflecting savings due to eliminating the aforementioned factors, as well as reductions due to fewer legal violations like running red lights), and 90% safer at the 90% market penetration rate (reflecting the near-elimination of human error as a primary crash cause, thanks to improving vehicle automation technology). Pedestrian and bicycle crashes (with motor vehicles) are assumed to enjoy half of the AV safety benefits, since just one of the two crash parties (the driver) relies on the AV technology. Similarly, motorcycles may not enjoy autonomous status for a long time (and their riders may be reluctant to relinquish control), and around half of all fatal motorcycle crashes do not involve another vehicle. Therefore, motorcycles are assumed to experience just a 25% decline in their crash rates, relative to the declines experienced by other motor vehicles. Crash costs were estimated first based on their economic consequences, using National Safety Council (National Safety Council, 2012) guidance, and then on higher comprehensive costs, as recommended by the USDOT (Trottenberg, 2011), to reflect pain and suffering and the full value of a statistical life.

While this analysis estimates that safety improvements will be greater than new safety risks due to automation, it is possible that new risks will be greater for some system users under certain circumstances, particularly at early technology stages. Lin argues that increased safety to some users at the expense of others is not necessarily a clear-cut benefit, even if net safety risks to the whole population is lower (Lin, 2013). Readers should note that this analysis acknowledges such dilemmas are present, even though it assesses net safety improvements, rather than potential improvements for some types of crashes and added complications for other crash types.

2.9. Congestion reduction

Shrank and Lomax's congestion impact projections (Schrank et al., 2012) for 2020 are used here as a baseline. They assumed a $17 per person-hour value of travel time, $87 per truck-hour value of travel time, and statewide average gas prices in 2010. They estimated that 40% of the nation's roadway congestion occurs on freeway facilities (with the remainder on other streets), and that by 2020, U.S. travelers will experience around 8.4 billion hours of delay while wasting 4.5 billion gallons fuel (due to congestion), for an annual economic cost of $199 billion.

Here, it is assumed that AVs are equipped with CACC and traffic-flow-smoothing capabilities. At the 10% AV-market penetration level, freeway congestion delays for all vehicles are estimated to fall 15%, mostly due to smoothed flow and bottleneck reductions. This is lower than Atiyeh (2012) suggests, in order to reflect induced travel, though additional congestion benefits may be realized (due to fewer crashes, a small degree of increased capacity from CACC, and smarter vehicle routings). At the 50% market penetration level, a cloud-based system is assumed to be active (Atiyeh suggests 39% congestion improvements from smoothed flow), and further capacity enhancements of 20% may be realized. Furthermore, with crashes falling due to safety improvements, another 4.5% in congestion reduction may be obtained. Again, induced travel will counteract some of these benefits, and a 35% delay reduction on freeways is estimated in this analysis. Finally, at the 90% level, freeway congestion is assumed to fall by 60%, with the near doubling of roadway capacity (Shladover et al., 2012) and dramatic crash reductions. However, readers should note that capacity and delay are not linearly related and congestion abatement may be even greater than these predictions at the with 90% market penetration.

At the arterial-roadway level, congestion is assumed to experience much lower benefits from AVs (without near-complete market penetration and automated intersection management (Dresner and Stone, 2008), since delays emerge largely from conflicting turning movements, pedestrians, and other transportation features that AV technologies cannot address as easily. Therefore, arterial congestion benefits are assumed to be just 5% at the 10% market-penetration level, 10% at the 50% penetration rate, and 15% at 90% market penetration. AV fuel efficiency benefits are assumed to begin at 13%, increasing to 25% with 90% market penetration, due to better route choices, less congestion, road-train drag reductions (from drafting), and more optimal drive cycles. Non-AVs on freeways are assumed to experience 8% fuel economy benefits during congested times of day under a 10% market penetration, and 13% at the 50% and 90% penetration levels. For simplicity, this analysis assumes that all induced travel's added fuel consumption will be fully offset by AVs' fuel savings benefits during non-congested times of day.

2.10. Parking

Parking savings comprise the final monetized component of this analysis. Litman (2012) estimates that comprehensive (land, construction, maintenance and operation) annual parking costs are roughly $3300 to $5600 per parking space in central business districts (CBDs), $1400 to $3700 per parking space in other central/urban areas, and $680 to $2400 per space in suburban locations. So simply moving a parking space outside of the CBD may save nearly $2000 in annualized costs, while moving one to a suburban location may save another $1000. In addition to self-parking AVs allowing for moved spaces, fewer overall spaces should be needed thanks to car sharing. Therefore, while not every AV will result in a moved or eliminated parking space, this analysis assumes that $250 in parking savings will be realized per new AV (thanks in part to the earlier assumption of 10% of AVs being publicly shared).

2.11. Summary economic impacts

Table 2 summarizes all of these estimated impacts, suggesting *economic* benefits reaching $196 billion ($442 billion, comprehensive) with a 90% AV market penetration rate. Meaningful congestion benefits are estimated to accrue to all travelers early on, while the magnitude of crash benefits grows over time (and accrues largely to AV owners/users). For example, congestion savings represent 66% of benefits, and crash savings represent 21% of benefits – at the 10% market penetration level, versus 31% and 54% of benefits, respectively, at the 90% penetration rate. When comprehensive crash costs are included, overall crash savings jump by more than a factor of three.[2]

These results are consistent with Manyika et al.'s findings (Manyika et al., 2013), which estimate global AV impacts of $200 billion to $1.9 trillion by 2025 (assuming that 5–20% of all driving is either autonomous or semi-autonomous, and valuing the lowered burdens of in-vehicle travel time [at least for drivers, who can now perform other activities en route]). If the 10% market penetration estimates used here are scaled globally (at least within the developed world), and the lowered burden of in-vehicle time is added, overall economic benefits are likely to fall within Manyika et al.'s range.

Additional monetized congestion benefits may be realized beyond the values shown in Table 2, due to falling values of travel time. For example, an hour stuck driving in traffic may be perceived as more onerous than an hour spent being driven by an AV.

2.12. Privately realized benefits

While Table 2 illuminates AVs' social benefits, it is also important to anticipate the privately realized benefits of AV ownership and use. These benefits are assessed using Table 2's assumptions at the 10% market penetration and a $10,000 added purchase price, taking into account monetary savings from reduced fuel use and insurance, along with several levels of daily parking savings and (hourly) travel time savings.

Privately realized benefits were estimated using Table 2's assumptions for the $10,000 purchase price. These were first compared to 50% insurance cost savings from a base of $1000 per year and 13% fuel savings from a base of $2400 per year (American Automobile Association, 2012) were both assumed over a 15-year vehicle life. Parking costs of $250 were next are added, which represents about $1 per work day. Finally, driven time under autonomous operation was added under $1 per hour and $5 per hour assumptions, with total annual vehicle hours traveled estimated based on U.S. average vehicle miles traveled (10,600 miles per year) divided by an assumed average speed of 30 mph (Federal Highway Administration, 2013). Privately realized internal rates of return were also compared to a higher added-technology price, of $37,500.

This results in the ranges of benefits shown in Table 3, across various purchase prices, values of time and parking costs:

At current high technology costs of $100,000 or more, benefits are mostly small compared to purchase prices, except for individuals with very high values of time. Once prices come down to $37,500, persons with high values of travel time and/or parking costs may find the technology a worthwhile investment. Only at the $10,000 added price does the technology become a realistic investment for many, with even the $1 per hour time value savings and $1 daily parking cost savings generating an 11% rate of return for AV owners.

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[2] Comprehensive crash costs include indirect economic factors, like the statistical value of life and willingness-to-pay to avoid pain and suffering, with values recommended by the USDOT (Trottenberg, 2011).

Table 2
Estimates of annual economic benefits from AVs in the United States.

	Assumed market shares		
	10%	50%	90%
Crash cost savings from AVs			
Lives saved (per year)	1100	9600	21,700
Fewer crashes	211,000	1,880,000	4,220,000
Economic cost savings	$5.5 B	$48.8 B	$109.7 B
Comprehensive cost savings	$17.7 B	$158.1 B	$355.4 B
Economic cost savings per AV	$430	$770	$960
Comprehensive cost savings per AV	$1390	$2480	$3100
Congestion benefits			
Travel time savings (M hours)	756	1680	2772
Fuel savings (M gallons)	102	224	724
Total savings	$16.8	$37.4	$63.0
Savings per AV	$1320	$590	$550
Other AV impacts			
Parking savings	$3.2	$15.9	$28.7
Savings per AV	$250	$250	$250
VMT increase	2.0%	7.5%	9.0%
Change in total # vehicles	−4.7%	−23.7%	−42.6%
Annual savings: Economic costs only	$25.5 B	$102.2 B	$201.4 B
Annual savings: Comprehensive costs	$37.7 B	$211.5 B	$447.1 B
Annual savings per AV: Economic costs only	$2000	$1610	$1760
Annual savings per AV: Comprehensive costs	$2960	$3320	$3900
Net present value of AV benefits minus added purchase price: Economic costs only	$5210	$7250	$10,390
Net present value of AV benefits minus added purchase price: Comprehensive costs	$12,510	$20,250	$26,660
Assumptions			
Number of AVs operating in U.S.	12.0 M	45.1 M	65.1 M
Crash reduction fraction per AV	0.5	0.75	0.9
Freeway congestion benefit (delay reduction)	15%	35%	60%
Arterial congestion benefit	5%	10%	15%
Fuel savings	13%	18%	25%
Non-AV following-vehicle fuel efficiency benefit (freeway)	8%	13%	13%
VMT increase per AV	20%	15%	10%
% of AVs shared across users	10%	10%	10%
Added purchase price for AV capabilities	$10,000	$5000	$3000
Discount rate	10%	10%	10%
Vehicle lifetime (years)	15	15	15

Table 3
AV owners' privately realized internal rates of return (from 0% to 10% market share).

Development stage	Estimated added costs	Benefits (daily parking and hourly value of travel time savings) (%)							
		$0 and $0	$0 and $1	$1 and $1	$5 and $1	$1 and $5	$5 and $5	$5 and $10	$10 and $10
Current	$100k+	−19	−17	−15	−11	−9	−6	−2	0
Initial price	$37.5k	−12	−8	−6	0	2	6	12	16
Mass production	$10k	3	8	11	23	28	38	56	68

This report does not attempt to quantify or monetize several of the impacts discussed earlier. For example, the potential benefits to the newly mobile are not forecasted, nor are the health impacts of potentially diminished walk distances, thanks to self-park, door-to-door services. Many of the nation's 240,000 taxi drivers and 1.6 million truck drivers (Bureau of Labor Statistics, 2012) could be displaced by AV technologies, while greenhouse gas emissions, infrastructure needs, and rates of walking may fall or rise, depending on the induced VMT. Increased sprawl or automobile-style development could also result, as projected by Laberteaux (2014). Such impacts are not included in the analysis.

While exact magnitudes of all impacts remain uncertain, this analysis illustrates the potential for AVs to deliver substantial benefits to many, if not all, Americans, thanks to sizable safety and congestion savings. Even at 10% market penetration, this technology has the potential to save over 1000 lives per year and offer tens of billions of dollars in economic gains, once added vehicle costs and possible roadside hardware and system administration costs are covered.

3. Barriers to implementation

AVs present many opportunities, benefits and challenges, while ushering in behavioral changes that effect how travelers interact with transportation systems. The speed and nature of any transition to a largely AV system are far from guaranteed;

they will depend heavily on AV purchase costs, as well as state and federal licensing and liability requirements. Moreover, AVs present some unusual risks, particularly from security and privacy standpoints. Even with a smooth and relatively rapid deployment that addresses security and privacy concerns, a system that optimally exploits AV capabilities requires special research efforts. The following discussion outlines several barriers that AVs face.

3.1. Vehicle costs

One barrier to large-scale market adoption is the cost of AV platforms. The technology needed for an AV includes the addition of new sensors, communication and guidance technology, and software for each automobile. Shchetko (2014) notes that Light Detection and Ranging (LIDAR) systems on top of many of today's AVs cost $30,000 to $85,000 each, and additional costs will accrue from other sensors, software, engineering, and added power and computing requirements. To be reasonably affordable, future AVs may need to use non-LIDAR sensors or LIDAR prices must fall dramatically, which auto parts manufacturer Valeo hopes to accomplish by producing automotive LIDAR devices for just $1000 by 2016 (Shchetko, 2014). Dellenback (2013) estimates that most current civilian and military AV applications cost over $100,000. This is unaffordable for most Americans, with 2012 sticker prices for the top 27 selling vehicles in America (Boesler, 2012) ranging from $16,000 to $27,000. More cost-effective approaches are possible, with Chengalva et al. (2009) paying less than $20,000 in total hardware costs to build an AV reaching the semi-final rounds of DARPA's 2007 Urban Challenge.

As with electric vehicles, technological advances and large-scale production promise greater affordability over time. Dellenback (2013) estimates that added costs may fall to between $25,000 and $50,000 (per AV) with mass production, and likely will not fall to $10,000 for at least ten years. Insurance, fuel, and parking-cost savings may cover much of the added investment. Typical annual ownership and operating costs ranged from $6000 to $13,000, depending on vehicle model and mileage (American Automobile Association, 2012), with insurance and fuel costs around $900 to $1000 and $1100 to $3700, respectively. These costs may fall by 50% for insurance and 13% for fuel costs and substantial further savings may be realized in expensive parking environments.

If AV prices come close to conventional vehicle prices, research suggests a ready and willing market for AVs. J.D. Power and Associates' recent survey (J.D. Power and Associates, 2012) found that 37% of persons would "definitely" or "probably" purchase a vehicle equipped with autonomous driving capabilities in their next vehicle, though the share dropped to 20% after being asked to assume an additional $3000 purchase price. This is the eventual price increase estimated by Volvo senior engineer Erik Coelingh for AV capabilities (Economist Technology Quarterly, 2012), though early-sales' costs will likely be much higher for early adopters, as noted above. Hensley et al. (2009) noted that electric vehicle costs have been declining by 6% to 8% annually, suggesting that it may be 15 years at 8% annual cost reduction to go from a $10,000 AV mark-up (perhaps possible in five to seven years' time after initial introduction) to a $3000 mark-up (20–22 years after introduction). For comparison, as of February 2013, adding all available driver-assist features, adaptive cruise control, safety options (including night vision with pedestrian detection), and the full "technology package" increases a BMW 528i sedan's purchase price by $12,450, from a base MSRP of $47,800 (BMW of North America, 2013). While these features provide guidance and a degree of automation for certain functions, full control remains with the human driver.

As AVs migrate from custom retrofits to mass-produced designs, it is possible that these costs could fall somewhere close to Coelingh and J.D. and Associates' $3000 mark, and eventually just $1000 to $1500 more per vehicle (KPMG and CAR, 2012). Nevertheless, cost remains high and is therefore a key implementation challenge, due to the current unaffordability of even some of the more basic technologies.

3.2. AV certification

As of July 2014, California (SB 1298), and Nevada (AB 511) have enacted legislation allowing AV certification, while Florida's CS/HB 1207, Michigan's SB 0169, and Washington, D.C.'s B19-0931 have enabled AV testing. Related legislation is pending in Georgia, Hawaii, Louisiana, Maryland, Massachusetts, Minnesota, New Jersey, New York, South Carolina, South Dakota, and Washington. States have thus far declined to set many specific restrictions, directing their state DMVs to establish regulatory certification and provisional testing standards. This legislative guidance has varied significantly, from state to state. For example, Nevada's original legislation (since amended) contained just 23 lines of definitions and broad guidance to its DMV, while California's is a more detailed six pages and similar direction to its DMV (to establish safety and testing specifications and requirements). Without a consistent certification framework and standardized set of safety for acceptance, AV manufacturers may be faced with regulatory uncertainty and unnecessary overlap, among other issues.

California's more detailed legislative content provides concrete requirements for AVs. SB 1298 states specific requirements for AV testing on public roads, including insurance bonding, the ability to quickly engage manual driving, fail-safe systems in case of autonomous technology failure, and sensor data storage prior to any collision. This legislation calls upon the California DMV to consider possible regulations for a broad array of issues, including the total number of AVs using California's public roadway system, AV registration numbers, AV operator licensing and requirements, possible revocation of AV licenses, and the denial of licensing. California's legislation contains a subsection requiring public hearings on driverless AVs and directs the DMV to enact stricter oversight for such AVs. California has recently granted permits to Google, Audi and Mercedes Benz for testing of AVs on public roads, with a final rulemaking establishing certification standards for AV sales to the general public is expected by 2015.

Nevada has also processed AV testing permits for Google, Continental, and Audi, for operation on public roads. Nevada's certification requirements include a minimum of 10,000 autonomously driven miles and documentation of vehicle operations in complex situations. Such situations reflect use of various traffic control devices (including roundabouts, traffic signals, signs, school zones, crosswalks and construction zones); the presence of pedestrians, cyclists, animals, and rocks, and recognition of speed limit variations, including temporary restrictions and variable school-zone speed limits. Furthermore, Nevada can grant testing permits subject to certain geographic and/or environmental limitations (e.g., autonomous operation only on the state's interstates, for daytime driving free of snow and ice, etc.), and California is acting similarly. This highlights the necessity for state agencies to ensure that AVs are able to safely operate in any situation where they might be driven, and the incremental nature by which automation technology is being introduced. While the proactive strategies pursued by these states is commendable, if many disparate versions of these crucial regulatory issues emerge (across distinct states), AV manufacturers will incur delays and increased production and testing costs.

Drivers licensed in one U.S. state are able to legally operate a vehicle in other states through reciprocity agreements, as outlined in the state Driver License Compact, constituting agreements between all but five U.S. states (Georgia, Wisconsin, Massachusetts, Michigan, and Tennessee). The language (State of Montana, 2011) states: "It is the policy of each of the party states to… make the reciprocal recognition of licenses to drive… in any of the party states". Smith (2012) notes that current law probably does not prohibit automated vehicles in states without explicit AV licensing, though failure to clarify regulations may "discourage their introduction or complicate their operation".

3.3. Litigation, liability and perception

Once AVs become certified for safe operation by a state DMV or other regulatory agency, many new insurance and liability issues arise, including persuading insurance providers that the technology will work properly, in all driving environments. Even with near-perfect autonomous driving, there may be instances where a crash is unavoidable. For example, if a deer jumps in front of the car, does the AV hit the deer or run off the road? How do actions change if, instead of a deer, there is another car, a heavy-duty truck, a motorcyclist, bicyclist, or pedestrian? Does the roadside environment and/or pavement wetness factor into the decision? What if the lane departure means striking another vehicle? With a split second for decision-making, human drivers typically are not held at fault when responding to circumstances beyond their control, regardless of whether their decision was the best. In contrast, AVs have sensors, visual interpretation software, and algorithms that enable them to potentially make more informed decisions. Such decisions may be questioned in a court of law, even if the AV is technically not "at fault". Other philosophical questions also arise, like to what degree should AVs prioritize minimizing injuries to their occupants, versus other crash-involved parties? And should owners be allowed to adjust such settings?

Regardless of how safe AVs eventually become, there is likely to be an initial perception that they are potentially unsafe because the lack of a human driver. Perception issues have often been known to drive policy and could delay implementation. Moreover, if AVs are held to a much higher standard that human drivers, which is likely given perception issues, AV costs will rise and fewer people will be able to purchase them. Some steps have been made to account for liability concerns. California law (Center for Information and Society, 2012) requires 30 s of sensor data storage prior to a collision to help establish fault, assuming that the AV has been programmed and tested properly. Other semi-autonomous technologies, such as parking assist and adaptive cruise control, will likely provide initial test cases that will guide how fully autonomous technologies will be held liable.

3.4. Security

Transportation policymakers, auto manufacturers, and future AV drivers often worry about electronic security. Computer hackers, disgruntled employees, terrorist organizations, and/or hostile nations may target AVs and intelligent transportation systems more generally, causing collisions and traffic disruptions. As one worst-case scenario, a two-stage computer virus could be programmed to first disseminate a dormant program across vehicles over a week-long period, infecting virtually the entire U.S. fleet, and then cause all in-use AVs to simultaneously speed up to 70 mph and veer left. Since each AV in the fleet represents an access point into such systems, it may be infeasible to create a system that is completely secure.

To understand the extent of this threat, it is important to view the problem from an effort-and-impact perspective and to recognize mitigation techniques commonly used in comparable critical infrastructure systems of national importance. According to Hickey (2012), vice president of software security firm Vínsula, current cyber-attacks are more commonly acts of espionage (gaining unauthorized access to a system for the purpose of information gathering) rather than sabotage (actively compromising a system's normal operation). Disrupting a vehicle's communication or sensors, for example, would require a more complex and sophisticated attack than one designed to simply gather information, and disrupting the vehicle's control commands would be harder still. Engineering an attack to simultaneously compromise a fleet of vehicles, whether from a point source (for example, compromising all vehicles near an infected AV) or from a system-wide broadcast over infected infrastructure would likely pose even greater challenges for a would-be attacker. Regardless, the threat is real and a security breach could have lasting repercussions.

Fortunately, robust defenses should make attacks even more difficult to stage. The U.S. has demonstrated that it is possible to maintain and secure large, critical, national infrastructure systems, including power grids and air traffic control systems. The National Institute of Standards and Technology (NIST) is currently developing a framework to improve critical infrastructure cyber security, and recommendations that stem from this framework may be incorporated into automated and connected vehicle technologies. While security measures for personal computers and Internet communication were implemented largely as an afterthought, and in an ad-hoc manner (Hickey, 2012), V2V and V2I protocols have been developed with security implemented in the initial development phase (National Highway Traffic Safety Administration, 2011). These and other security measures (like the separation of mission-critical and communication systems) should make large-scale attacks on AVs and related infrastructure particularly difficult. Though Grau (2012) and Hickey (2012) both acknowledge that there is no ‘‘silver bullet’’, such measures make attacks much harder to pull off while limiting the damage that can be done.

3.5. Privacy

California-based consumer education and advocacy organization Consumer Watchdog raised privacy concerns during a recent round of AV-enabling legislation (Brandon, 2012). Such concerns are likely to grow as AVs and non-autonomous connected vehicles become more mainstream and data sharing becomes commonplace. This gives rise to five data-related questions: Who should own or control the vehicle’s data? What types of data will be stored? With whom will these data sets be shared? In what ways will such data be made available? And, for what ends will they be used?

It is likely that crash data will be owned or made available to AV technology suppliers, since they will likely be responsible for damages in the event of a crash, provided that the AV was at fault. If a human is driving a vehicle with autonomous capabilities when the crash occurs, however, privacy concerns arise. No one wants his/her vehicle’s data recorder being used against them in court, though this is merely an extension of an existing issue: around 96% of new passenger vehicles sold in the U.S. today have similar (but less detailed) event data recorders that describe vehicle actions taken in the seconds prior to and following a crash, and NHTSA is considering mandating event data recorders on all new vehicles under 8500 lbs. by late 2014 (National Highway Traffic Safety Administration, 2012b). While some states restrict insurance company access to such data (and require a warrant for access), in much of the U.S. data ownership and control remain undefined (Kaste, 2013).

Providing AV travel data, such as routes, destinations, and times of day, to centralized and governmentally controlled systems is likely more controversial, particularly if the data is recorded and stored. While movement tracking of individuals already occurs to some degree through roadside Bluetooth sensors and cell phone tower triangulation, continual monitoring could take this phenomenon to a whole new level. Without proper safeguards, this data could be misused by government employees for tracking individuals, or provided to law enforcement agencies for unchecked monitoring and surveillance. Vehicle travel data has wide-ranging commercial applications that may be disconcerting to individuals, such as targeted advertising.

At the same time, responsible dissemination and use of AV data can help transportation network managers and designers. This data could be used to facilitate a shift from a gas tax to a VMT fee, or potentially implement congestion pricing schemes by location and time of day. Those who program traffic signal systems, for example, could use such data to improve system efficiency and trip quality for travelers. In contrast, continuously connected AVs or connected conventional vehicles could illuminate continuous vehicle paths and speed changes, and so inform signal systems operational changes. Moreover, such data could be used to assist transportation planners evaluating future improvements, leading to more effective investment choices and transportation policies. Law enforcement could also benefit from such data, and commercial profits from advertising may drive down AV prices. Sharing of this data has tradeoffs, and any decisions to enhance traveler privacy should be balanced against the benefits of shared data.

3.6. Missing research

While AVs may be commercially available within five years, related research lags in many regards. Much of this is due to the uncertainty inherent in new contexts: with the exception of a few test vehicles, AVs are not yet present in traffic streams and it is difficult to reliably predict the future following such disruptive paradigm shifts. Moreover, technical developments along with relevant policy actions, will effect outcomes and create greater uncertainty. With these caveats in mind, it is useful to identify the critical gaps in existing investigations to better prepare for AVs’ arrival.

One of the most pressing needs is a comprehensive market penetration evaluation. As KPMG and CAR (2012), Google (O’Brien, 2012), Nissan (Nissan, 2013), Volvo (Carter, 2012), and others make clear, AVs probably will be driving on our streets and highways within the next decade, but it is uncertain when they will comprise a substantial share of the U.S. fleet. More meaningful market penetration estimates should attach dates and percentages to aggressive, likely, and conservative AV-adoption scenarios. This would provide transportation planners and policy-makers with a reasonable range of outcomes for evaluating competing infrastructure investments, AV policies, and other decisions.

Other important research gaps have been identified, with broad topic areas outlined at the 2014 Automated Vehicles Symposium (Transportation Research Board, 2014), as follows:

- Automated transit and shared mobility.
- Regional planning and modeling.
- Roadway management and operations.

- Truck automation opportunities.
- Legal accelerators and brakes.
- Automated vehicle human factors.
- Near-term deployment opportunities.
- Personal vehicle automation commercialization.
- Automation systems operational requirements.
- Road infrastructure needs of connected-automated vehicles.

Many important, and frequently crosscutting, questions arise from within each of these topic areas. For example, if driverless taxis become legal and commercially and technologically viable, they could serve many trips currently served by privately owned vehicles. This would reduce parking and ownership needs, and have impacts that cut across the transit and shared mobility, regional planning, roadway management, and commercialization focus areas. As long as these and other crucial questions go unanswered, the nation will be hampered in its ability to successfully plan for and introduce AVs into the transportation system.

4. Policy recommendations

Given the apparent promise of AVs, it seems wise for policymakers and the public to seek a smooth and intelligently planned introduction for, and transition to, this new technology. The state of AV technology seems likely to advance with or without legislative and agency actions at the federal level. However, the manner in which AV technologies progress and will eventually be implemented depends heavily on these efforts. Intelligent planning, meaningful vision, and regulatory action and reform are required to address the various issues discussed above. This report recommends three concrete actions to address these issues:

4.1. Expand federal funding for autonomous vehicle research

Car manufacturers and others have invested many resources in the research and development of AV technologies. Meanwhile, there is a relatively little understanding of how such vehicles will affect the transportation system. This paper has highlighted key missing links in AV research, including the incorporation of market penetration scenarios in planning efforts, as well as topic areas identified at the Automated Vehicle Symposium. A strong federal role in funding this research, similar to the strong federal role in funding numerous technological innovations throughout our nation's history, is essential.

Other gaps in understanding and technology needs will become apparent as AVs enter the marketplace. Due to the potential national benefits from overcoming these gaps, it becomes imperative to involve agencies such as the U.S. Department of Transportation (USDOT), the National Science Foundation, and the Department of Energy. State DOTs, local transportation agencies and planning organizations, and other stakeholders could also help fund such research, to enable regions and nations to anticipate and more effectively plan for AV opportunities and impacts.

4.2. Develop federal guidelines for autonomous vehicle certification

To facilitate regulatory consistency, the USDOT should assist in developing a framework and set of national guidelines for AV certification at the state level. Though NHTSA has developed broad principles for AV testing (National Highway Traffic Safety Administration, 2013), certifying AVs for use by the general public is currently a state endeavor at this time and should have some federal guidance in order to ensure continuity. With similar sets of standards in place, states will be able to pool efforts in developing safety, operations, and other requirements. One framework for this effort could be the USDOT's (Federal Highway Administration, 2009a) Manual on Uniform Traffic Control Devices (MUTCD). This approach promotes a single document for adoption by all states, with each state making a limited number of modifications to suit specific, local needs. Under such a framework, AV manufacturers will be better able to meet detailed national requirements and just a handful of possible individual state requirements, rather than trying to match 50 potentially different sets of testing requirements across states.

Existing state certification efforts should be seen as a complement to national efforts, which could streamline AV certification and testing, enabling more efficient application of both public and private resources. Policy makers should also consider potential regulatory downsides and the effects of excessive caution, which may be harmful to technological advancement. Moreover, such AV certification consistencies will likely help limit AV product liability, as argued by Kalra et al. (2009).

4.3. Determine appropriate standards for liability, security, and data privacy

Liability, security, and privacy concerns represent a substantial barrier to widespread implementation of AV technologies. The sooner federal and state governments address these issues the more certainty manufactures and investors will have in pursuing development. Liability standards will need to strike the balance between assigning responsibility to manufacturers and technologists without putting undue pressure on their products. Robust cyber security to address the vulnerability of these systems will help the industry develop ways to prevent outside attacks.

Consumers of AV technology will likely have some concerns about the use and potential abuse of data collected from their personal travel. Therefore, AV-enabling legislation should consider privacy issues to balance these legitimate concerns against potential data-use benefits. Since vehicles will inevitably cross state boundaries, federal regulation needs to establish parameters regarding what types of AV data should be shared, with whom it should be shared, in what way the data will be made available, and for what ends it may be used – rather than take a default (no action) position, which will likely result in few to no privacy protections.

5. Conclusions

The idea of a driverless car may seem a distant possibility, but automation technology is improving quickly and some semi-autonomous features are already offered on current vehicle models. This new technology has the potential to reduce crashes, ease congestion, improve fuel economy, reduce parking needs, bring mobility to those unable to drive, and over time dramatically change the nature of U.S. travel. These impacts will have real and quantifiable benefits. Based on current research, annual economic benefits could be in the range of $27 billion with only 10% market penetration. When including broader benefits and high penetration rates, AVs have the potential to save the U.S. economy roughly $450 billion annually. While these estimates do not include some of the associated costs and externalities (like emissions, employment, and residential changes), the potential for a dramatic change in the nature and safety of transportation is very possible.

Potential benefits are substantial but significant barriers to full implementation and mass-market penetration remain. Initial AV technology costs will likely be unaffordable to most Americans. States are currently pursuing their own licensing and testing requirements, which may lead to a disparate patchwork of regulations and requirements without federal guidance. A framework for AV liability is largely absent, creating uncertainty in the event of a crash. Security concerns should be examined from a regulatory standpoint to protect the traveling public, and privacy issues must be balanced against data uses. Auto manufacturers have shown their interest in AVs by investing millions of dollars to make self-driving vehicles. Policy makers should begin supporting research into how AVs could affect transportation and land use patterns, and how to best alter our transportation system to maximize their benefits while minimizing any negative consequences of the transition to a largely autonomous fleet of motor vehicles.

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