PREPARING A NATION FOR AUTONOMOUS VEHICLES: OPPORTUNITIES, BARRIERS AND POLICY RECOMMENDATIONS FOR CAPITALIZING ON SELF-DRIVEN VEHICLES

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The following paper is a pre-print, the final publication can be found in *Transportation Research Part A* 77: 167-181, 2015.

Key Words: Vehicle automation, autonomous vehicles, cost-benefit analysis, safety, congestion, market penetration, licensing, liability, privacy, cyber security

Abstract

Autonomous vehicles (AVs) represent a potentially disruptive and beneficial change to the way in which we travel. This new technology has the potential to impact personal travel across a wide array of impacts including 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 likely on the order of $2,000 per year per AV, or $3,000 eventually increasing to nearly $5,000 when comprehensive crash costs are accounted for.

Yet barriers to implementation and mass-market penetration remain. Initial costs will likely be unaffordable and licensing and testing standards in the U.S. are being developed at the state level, rather than adopting a national framework, which may lead to inconsistencies across states. Liability regimes remain undefined, security concerns linger, and absent new privacy standards, a default lack of privacy for personal travel may become the norm. Finally, with the advent of this new technology, many impacts, interactions with other components of the transportation system, and implementation details remain uncertain. To address these concerns, research in these areas should be expanded, and the U.S. and other countries should create nationally recognized licensing structures for AVs, and determine appropriate standards for liability, security, and data privacy.

INTRODUCTION

Over the past 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 cars 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 even further by creating almost fully autonomous vehicles (AVs) that can navigate highways and urban environments with almost no direct human input. Assuming that these technologies become successful and enter the mass market, AVs have the potential to dramatically change transportation. This paper serves as an introduction for transportation professionals and policymakers to AV technology, potential impacts, and hurdles.

AVs may fundamentally alter transport systems. They have the potential to avert deadly crashes, provide mobility to the elderly and disabled, increase road capacity, save fuel, and lower harmful 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, parking needs, land use patterns, and trucking and other activities will be impacted.

The proliferation of AVs is far from guaranteed. In addition to technological challenges, other hurdles remain. High costs hamper large-scale production and mass consumer availability, and complex questions remain relating to legal, liability, privacy, licensing, security, and insurance regulation (e.g. KPMG & CAR 2012, ETQ 2012, Grau 2012). While individual U.S. states have been advancing AV legislation through incremental measures (CIS 2012), the federal government's recent focus has been on setting automation standards for single and combined automation function applications, rather vehicles with limited or fully automated control.

At the 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). Assuming an additional five years for prices to drop for some degree of mass-market penetration, AVs may be commonplace by 2022, 18 years after the first successful tests. Whether or not consumer adoption comes this fast, policymakers still need to begin to address the multiple unprecedented issues that AVs could bring.

AVs Today

In 2004 DARPA's (Defense Advanced Research Projects Agency) Grand Challenge's was launched with the goal of demonstrated AV technical feasibility by navigating a 150-mile route. While the best team completed just over 7 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 fixed and moving obstacles, together which provided realistic, every-day-driving scenarios (DARPA 2012). As of April 2013 Google's self-driving cars have driven over 435,000 miles on California public roads, and numerous manufacturers – including Audi, BMW, Cadillac, Ford, GM, Mercedes-Benz, Nissan, Toyota, Volkswagen, and Volvo – have begun testing driverless systems. Some features necessary for full vehicle automation are now commercially available, including adaptive cruise control (ACC), lane departure warnings, collision avoidance, parking assist systems, and on-board navigation. Europe's CityMobile2 project is currently demonstrating low-speed AV transit applications in dedicated areas in five cities. Additionally, AVs are becoming increasingly common in other sectors, with military, mining and agricultural applications (ETQ 2012), all of which demonstrate the potential for AVs in "traditional" roadway environments.

Paper Organization

AVs should have substantial impacts on the transportation system, including benefits to those not directly using AVs. However, barriers remain to well-managed large-scale AV market penetration. This research illuminates these barriers and suggests federal-level policy recommendations for an intelligently planned transition as AVs become a growing share of our transportation system.

As such, this paper contains three major sections:

- AVs' Potential Benefits,
- Barriers to Implementation, and
- Policy Recommendations.

The first section reviews existing literature to ascertain system benefits and impacts, in regards 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 paper's second section investigates barriers to adoption, largely from a consumer and regulatory standpoint, rather than technical feasibility. The final section proposes policy recommendations to directly address potential barriers identified earlier.

AVs' POTENTIAL BENEFITS

AV operations are inherently different from human-driven vehicles. They may 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 identified in existing research. The exact extent of these benefits remains unknown, but this paper attempts to estimate these benefits to gauge their magnitude, under varying market penetration levels.

Safety

Autonomous vehicles have the potential to dramatically reduce crashes. More than 40% of fatal crashes involve alcohol, distraction, drug involvement and/or fatigue (NHTSA 2012). Self-driven vehicles should not fall prey to human failings, suggesting the potential for at least a 40% fatal crash rate reduction, everything else 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 percent of all crashes (NHTSA, 2008). Even when the vehicle or roadway environment is the critical reason behind a crash, human factors such as inattention, distraction, or speeding regularly contribute to the crash occurrence and/or injury severity.

The scope of potential benefits is substantial. Over 30 thousand persons die each year in the U.S. in automotive collisions (NHTSA 2012), with 2.2 million crashes resulting in injury (NHTSA 2013). At $300 billion, the U.S. annual economic costs of crashes are three times higher than those of congestion (Cambridge Systematics 2011), and safety is highlighted as the #1 goal for transportation in Moving Ahead for Progress in the 21st Century (MAP-21).

While many driving situations are relatively easy for an autonomous vehicle to handle, designing a system that can perform safely in nearly every situation has been very challenging (e.g. Campbell et al. 2010). For example, recognition of humans in the roadway and object materials is both critical and more difficult for AVs than human drivers (e.g., ETQ 2012, and Farhadi et al., 2009). A person in a roadway may be many sizes, in different positions, and/or partly obscured, complicating sensor recognition. Additionally, evasive decisions should depend on whether an object in the vehicle's path is a large cardboard box or a large concrete block. 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.

There is also the possibility that some drivers will take their vehicles out of self-driving mode and take control. Ultimately, researchers predict that AVs will overcome many of the obstacles that inhibit them from accurately responding in complex environments. Hayes (2011) suggests that motor-vehicle fatality rates could eventually approach those seen in aviation and rail, about 1% of current rates; and KPMG and CAR (2012) advocate a goal of creating "crash-less cars", while noting that connected vehicle solutions could mitigate up to 80% of unimpaired crashes.

Congestion and Traffic Operations

Aside from safety improvements, 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 and reductions in traffic-destabilizing shockwave propagation. AVs may also use existing lanes and intersections more efficiently through shorter headways, coordinated platoons, and more efficient route choices.

These benefits will not happen automatically. Many congestion-saving improvements depend not only on automated driving capabilities, but also cooperative abilities through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. But significant congestion reduction could occur if the safety benefits alone are realized: 25% of congestion is attributable to traffic incidents, around half of which are crashes (FHWA 2005).

Multiple studies have investigated the potential for AVs to reduce congestion under differing scenarios. Congestion savings due to ACC measures and traffic monitoring systems could potentially smooth traffic flows by seeking to minimize freeway traffic accelerations and braking. This could increase fuel economy and congested traffic speeds respectively by 23% to 39% and 8% to 13%, for all vehicles in the freeway travel stream, depending on 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. Shladover et al. (2012) estimate that cooperative adaptive cruise control (CACC) deployed at a 10%, 50% and 90% market-penetration levels will increase lanes' effective capacities by around 1%, 21% and 80%, respectively. Headway reductions coupled with near-constant velocities produce more reliable travel times. Similarly, shorter start-up times and headways between vehicles at traffic signals mean that AVs could more effectively utilize green time at signals, improving intersection capacities.

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 to smooth traffic for all travelers. However, if just one out of two hundred vehicles are AVs, the impact will be greatly lessened. Also, if one AV is following another, the following AV can reduce the headway between the two vehicles, increasing 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 city-wide or regional coordination paradigms.

Travel-Behavior Impacts

Like safety and congestion, travel behavior may also change significantly. AVs may provide mobility for those too young to drive, the elderly and the disabled, thus generating new roadway 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; and the trucking industry may realize better fuel savings via road-trains, or even one day go driverless. Most of these ideas point toward more vehicle-miles traveled (VMT) and automobile-oriented development, though perhaps with fewer vehicles and parking spaces.

As of January 2013 in California, Florida and Nevada, legislation 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 fall away and AVs could be able 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 over the age of 65 and this demographic growing 50% faster than the overall population (U.S. Census 2011). Wood (2002) observes many drivers cope with physical limitations through self-regulation, avoiding heavy traffic, unfamiliar roads, night-time driving, and poor weather; while others stop driving altogether. AVs could facilitate personal independence and mobility while maintaining safety, thus further increasing automobile travel demand.

With increased mobility among the elderly and others, as well as lowered congestion delays, VMT increases may be expected along with associated congestion, emissions, and crash rates, unless demand-management strategies are thoughtfully implemented (Kockelman and Kalmanje 2006). Most AV benefits will likely exceed the negative impacts of added VMT. For example, even 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 traffic delays by 80%. Likewise, unless new AV travel is truly excessive, highway capacity improvements should accommodate the new/induced demand, thanks to AVs' congestion-mitigating features (like traffic smoothing algorithms) and capacity-increases (through CACC), as well as public-infrastructure investments (like V2I communication systems with traffics signals).

Already-congested traffic signals and other roadway infrastructure could be negatively impacted due to increased trip-making. 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 VMT is induced, the magnitude of AV benefits, and demand management strategies like road pricing. Emissions fall when travel is smooth, with Berry (2010) estimating that a 20% reduction in accelerations and decelerations should lead to 5% fuel consumption reductions, and resulting emissions, so while AVs may increase VMT, emissions per mile could fall.

Additional fuel savings may accrue through smart parking (Bullis 2011). In-vehicle systems could communicate with parking infrastructure and 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 business model may explode since users could simply order an on-demand taxi using mobile devices. Preliminary results (Fagnant and Kockelman 2013) using an agent-based model for assigning vehicles around a region in combination with NHTS data (FHWA 2009) indicate that a single shared AV could replace between nine and thirteen vehicles owned by individual households, without comprising current travel patterns. As shown in Figure 1, even in Seattle where vehicle use is more intense than national averages (PSRC 2006, FHWA 2009), just than 11% of vehicles are "in use" throughout the day, even at peak times, though usage rises to 16% if only including newer vehicles.

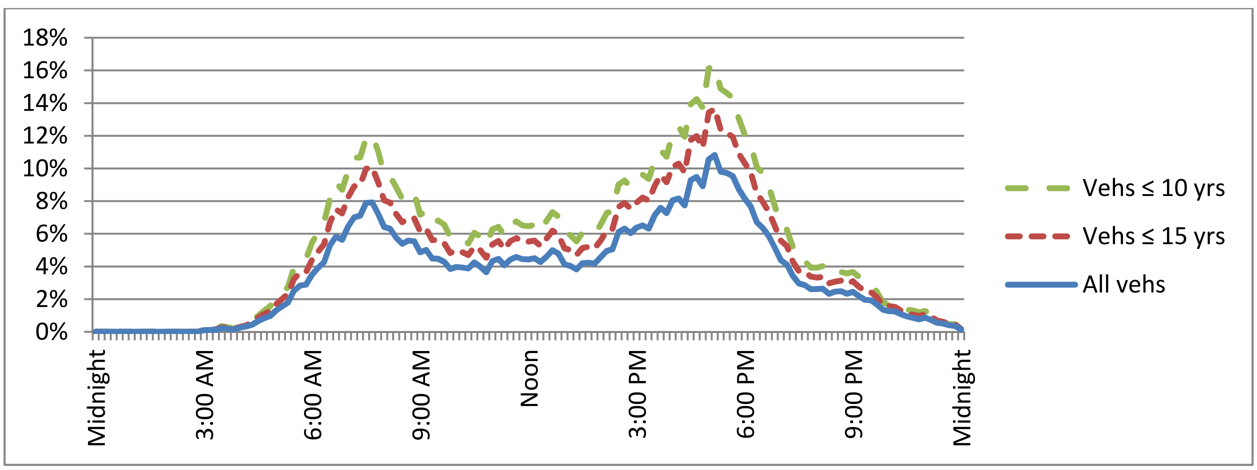

Figure 1: Vehicle Use by Time of Day and by Vehicle Age
(Source: PSRC 2006 household travel survey data)

Freight

Freight transport on and off the road will also be impacted. Mining company Rio Tinto already uses ten self-driving ore trucks, with plans to expand to 150 vehicles (ETQ 2012). Technologies that apply to autonomous cars can also apply to the trucking industry, increasing fuel economy and potentially the need for drivers. While workers must still load and unload cargo, long-distance driverless journeys may be made, with warehousing employees handling shipments at either end. This is not to claim all trucks will become driverless, but AVs could dramatically change the industry, enhancing productivity and lowering costs through reduced labor and improved service times. Political resistance may rise from labor groups as well as competing industries such as the freight railroads.

Higher fuel economies may emerge when using tightly coupled road-train platoons, from reduced air resistance. Lowered travel times from higher capacity networks may also be realized, as noted previously. Bullis (2011) estimates that 4-meter inter-truck spacings could reduce fuel consumption by 10 to 15 percent, and road-train platoons facilitate adaptive braking, enabling further fuel savings. Kunze et al. (2009) successfully demonstrated 10-meter headways between multiple trucks on public German motorways, and platooned Volvo trucks recently logged 10,000 km in Span (Newcomb, 2012).

Anticipating AV Impacts

Since AVs are only in the testing phase, it is difficult to precisely anticipate outcomes. Nevertheless, it is useful to roughly estimate likely impact magnitudes. Based on research estimates for potential impacts discussed above, this paper quantifies crash, congestion and other impacts for the U.S. transportation network (including parking, VMT, and vehicle counts). The analysis assumes three AV market penetration shares: 10%, 50% and 90%. These represent not only market shares, but also assume technological improvement over time, as it could take many years to see high penetration rates. This analysis is inherently imprecise, but gives the reader an order of magnitude estimate of AVs' broad economic and safety impacts.

VMT Change

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 fact that early adopters will generally have more pent-up demand for such vehicles than later buyers. Preliminary simulations (Fagnant and Kockelman 2013) underscore this idea, finding that a fleet of *shared* AVs serving around 65 thousand trips per day (representing over 2% of regional trips across a simulated city grid) cover 10.2% of their daily travel unoccupied, with this figure falling to 6.6% as the number of trips served doubles (thanks to a higher intensity of nearby pickups and drop-offs).

Additional VMT increases may be realized from induced demand as travel costs and congestion fall. In his thirty year review of literature, Cervero (2001) shows that the long term elasticity of VMT demand with respect to lane miles ranges from 0.47 to 1.0, averaging 0.74. This means that if regional vehicle lane mile increase by 1%, VMT should increase by around 0.74%. While AVs' congestion impacts are similar to increased lane miles, the effective capacity expansion is uniform, rather than targeted. That is, many areas today are uncongested, do not have latent demand and will likely continue to be so for the foreseeable future. This report does not account for induced travel due to latent demand, which may be stemmed with policies like congestion pricing. However, if even half of Cervo's elasticity estimates are applied, system-wide VMT could experience 37% growth by the 90% AV market-penetration level, from increased capacity effects.

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 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. Initial costs at the 10% market penetration level were assumed to add between $10,000 to the purchase price of a new vehicle, falling to $3,000 by the 90% market-penetration share, as noted later in this paper's Vehicle Cost section.

Safety

This analysis assumes 10% of AVs are shared (at all levels of penetration), and that a single shared AV serves ten times as many trips as a non-shared vehicle. U.S. crash rates and severity distributions for non-AVs are assumed constant and unchanged, based on NHTSA's 2011 values. As noted previously, over 90% of the primary factors behind crashes are due to human errors (NHTSA 2008), and 40% of fatal crashes involve driver alcohol or drug use, driver distraction and/or fatigue (NHTSA 2011). Therefore, AVs may be assumed 50% safer than non-AVs at the early, 10% market penetration rate (reflecting savings due to eliminating these factors, as well as fewer legal violations like running red lights), and 90% safer at the 90% market penetration rate (reflecting the near-elimination of human errors as primary crash causes, greater V2V use and improving technologies). Pedestrians and cyclists are assumed to enjoy half the AVs' safety benefits, since just the driver relies on the AV technology. Similarly, motorcyclists may be lagging adopters (with technological implementation issues too), 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 compared to other vehicles. Crash costs were estimated based on economic consequences (NSC 2012), and also on higher comprehensive costs, as recommended by the U.S. DOT (Trottenberg, 2011), to reflect pain, suffering and the statistical value life.

Congestion Reduction

Shrank and Lomax's (2011) congestion impact projections for 2020 were used as a baseline. They assumed a $17 per hour per traveler value of travel time, $87 per hour of truck travel time, and 2010 statewide average gas prices. They estimate that 40% of the nation's roadway congestion occurs on freeways (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 annual economic costs 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, to reflect induced travel, though additional congestion benefits may also be realized (due to fewer crashes, slight increased capacity from CACC, and better routing choices). At the 50% market penetration level, a cloud-based system is assumed to be in use (Atiyeh suggests 39% congestion improvements from smoothed flow), and further capacity enhancements of 20% may be realized (Shladover et al. 2012). Furthermore, with crashes falling due to safety improvements, another 4.5% congestion reduction may be obtained. Again, induced travel will counteract some of these benefits and a 35% freeway delay reduction is estimated. Finally, at the 90% level, freeway congestion is assumed to be reduced by 60% with the near doubling of roadway capacity 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 with 90% market penetration.

At the arterial-roadway level, congestion is assumed to benefit much less, 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 with 10% market penetration, and 13% at the 50% and 90% penetration levels. For simplicity, this analysis assumes induced travel's added fuel consumption is fully offset by AVs' fuel savings benefits during non-congested times.

Parking

Parking savings comprise this analysis' final monetized component. Litman (2012) estimates that comprehensive (land, construction, maintenance and operation) annual parking costs are roughly $3,300 to $5,600 per parking space in central business districts (CBDs), $1,400 to $3,700 per parking space in other central/urban areas, and $680 to $2,400 per space in suburban locations. Therefore moving a parking space outside of the CBD saves nearly $2,000 in annualized costs, while moving one to a suburban location save another $1,000. In addition to 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.

Summary Economic Analysis

Table 1 summarizes all of these estimated impacts, suggesting economic benefits reaching $189 billion ($434 billion, comprehensive) with a 90% AV market penetration rate. Meaningful congestion benefits are estimated to accrue early on, while crash benefits magnitude grows over time. For example, congestion savings represent 66% of benefits and crash savings represent 21% of benefits -- at the 10% market penetration level, versus 33% and 58% of benefits, respectively, at the 90% penetration rate. When including comprehensive costs, crash savings more than triple.

Table 1: 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)	1,100	9,600	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	$460	$1,080	$1,690
Comprehensive Cost Savings per AV	$1,470	$3,500	$5,460
Congestion Costs			
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	$1,400	$830	$970
Other AV Impacts			
Parking Savings	$3.0	$11.3	$16.3
Savings per AV	$250	$250	$250
VMT Increase	2.0%	7.5%	9.0%
Change in Total # Vehicles	-8.3%	-31.0%	-44.8%
Annual Savings: Economic Costs Only	**$25.3 B**	**$97.5 B**	**$189.0 B**
Annual Savings: Comprehensive Costs	**$37.6 B**	**$206.8 B**	**$434.7 B**
Savings Per AV: Economic Costs Only	**$2,110**	**$2,160**	**$2,910**
Savings Per AV: Comprehensive Costs	**$3,120**	**$4,580**	**$6,680**
Net Present Value of AV Benefits minus Purchase Price: Economic Costs Only	**$6,050**	**$11,430**	**$19,130**
Net Present Value of AV Benefits minus Purchase Price: Comprehensive Costs	**$13,730**	**$29,840**	**$47,810**

Assumptions			
Number of AVs Operating in U.S.	0.5	0.75	0.9
Crash Reduction Fraction per AV	15%	35%	60%
Freeway Congestion Benefit (delay reduction)	5%	10%	15%
Arterial Congestion Benefit	13%	18%	25%
Fuel Efficiency Benefit	8%	13%	13%
Non-AV Following-Vehicle Fuel Efficiency Benefit (Freeway)	20%	15%	10%
VMT Increase per AV	10%	10%	10%
% of AVs Shared across Users	10%	10%	10%
Added Purchase Price for AV Capabilities	$10,000	$5,000	$3,000
Discount Rate	10%	10%	10%
Vehicle Lifetime (years)	15	15	15

Table 1 illuminates AVs' social benefits, though it is also meaningful to examine privately realized AV benefits. Table 1's assumptions at the 10% market penetration level may be compared to $2,400 annual fuel costs and $1,000 insurance costs (AAA 2012), as well as various potential parking savings over 250 annual work days. Other benefits include valuations for time driven autonomously, with total annual vehicle hours traveled based on U.S. averages (14,200 miles per year) divided by an assumed average speed of 30 mph (FHWA 2013). This results in the ranges of benefits shown in Table 2, across various purchase prices, values of time and parking costs:

Table 2: Privately Realized Internal Rates of Return

Added Costs	**Benefits (Daily Parking & Hourly Value of Travel Time)**							
	$0 & $0	**$0 & $1**	**$1 & $1**	**$5 & $1**	**$1 & $5**	**$5 & $5**	**$5 & $10**	**$10 & $10**
$100k+	-19%	-16%	-14%	-10%	-7%	-5%	0%	2%
$37.5k	-12%	-7%	-6%	0%	4%	8%	16%	20%
$10k	3%	10%	13%	24%	34%	44%	68%	80%

At 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 $37,000, however, affluent 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 begin to truly become a realistic investment for many, with even a $1 per hour time value and $1 daily parking cost generating a 13% rate of return.

It should be noted that this report does not quantify or monetize several of the impacts discussed earlier. Benefits to the newly mobile are not forecast, nor health impacts from diminished walking distances. Some of the nation's 240,000 taxi drivers and 1.6 million truck drivers (BLS 2012) could be displaced by AVs, while emissions, infrastructure needs, and walking rates may change depending on induced VMT. Sprawl or automobile-style development could also result, which are not included in the analysis.

While exact magnitudes of all impacts remain uncertain, this analysis shows the potential for AVs to deliver substantial benefits to many, thanks to sizable safety and congestion savings. Even at 10% market penetration, this technology has the potential to save over a thousand lives per year and offer tens of billions of dollars in economic gains.

BARRIERS TO IMPLEMENTATION

AVs present many opportunities, benefits and challenges while ushering in new behavioral changes. The speed and nature of the transition to a largely AV system are far from guaranteed; they will depend heavily on purchase costs, as well as licensing and liability requirements. Moreover, AVs present security and privacy risks. Even with a smooth and rapid deployment that addresses security and privacy concerns, a system that optimally exploits AV capabilities requires special research efforts. The following outlines these barriers.

Vehicle Costs

One barrier to large-scale market adoption is AV cost. Technology needs include sensors, communication and guidance technology, and software for each automobile. KPMG and CAR

(2012) note that the Light Detection and Ranging (LIDAR) systems atop Google's AVs cost $70,000, with further costs from other sensors, software, engineering, and added power and computing requirements. Dellenback (2013) estimates that most current civilian and military AV applications cost over $100,000. This is simply unaffordable for most Americans, with 2012 sticker prices for the top 27 selling vehicles in America ranging from $16,000 to $27,000 (Boesler 2012).

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 and $50,000 with mass production, and likely will not fall to $10,000 for at least 10 years. Insurance, fuel, and parking-cost savings may cover much of the added investment, as noted earlier. Typical annual ownership and operating costs ranged from $6,000 to $13,000, depending on vehicle model and mileage (AAA 2012).

If AV prices come close to conventional vehicle prices, research suggests a ready market for AVs. J.D. Power and Associates' (2012) recent survey suggests 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. Volvo senior engineer Erik Coelingh estimates the same $3000 mark for AV capabilities (ETQ 2012), though early adopters will likely pay much more, as noted above. 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 (BMWUSA 2013). Of course, 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' $3,000 mark, or, eventually, perhaps just $1,000 to $1,500 more per vehicle (KPMG and CAR 2012). Nevertheless, cost remains a key implementation challenge, due to the current unaffordability of even some of the more basic technologies.

AV Licensing

As of July 2013, California, Nevada and Washington D.C. have enacted legislation allowing AV licensing, and Florida enables AV testing, with related legislation pending in another ten states (CIS 2013). States have thus far declined to set many specific restrictions, directing their state Departments of Motor Vehicles (DMVs) to establish regulatory licensing and provisional testing standards. This legislative guidance has varied significantly, from state to state. For example, Nevada's legislation contains just 23 lines of definitions and broad guidance to its DMV, while California's is a more detailed 6 pages and similar direction to their DMV (to establish safety and testing specifications and requirements). Without a consistent (or at least congruent) licensing framework and safety standardization for acceptance, AV manufacturers may face regulatory uncertainty and unnecessary overlap.

California's more detailed legislative content provides concrete requirements for AVs. It includes specific requirements for AV testing on public roads, including insurance bonding, the ability to quickly engage manual driving, failsafe systems in case of technology failure, and sensor data storage prior to any collision. The DMV must consider a broad array of regulations, including the number of AVs on California's public roads, AV registration numbers, AV operator licensing and requirements, possible AV license revocations, and licensing denial. Finally, the legislation requires public hearings and directs the DMV to enact strict AV oversight.

While California's DMV rulemaking is expected by 2015, Nevada has already processed AV testing licenses (on public roads) for Google, Continental and Audi. These licensing requirements include a minimum of 10,000 autonomously driven miles and documentation of vehicle operations in a number of complex situations. Furthermore, Nevada can grant testing licenses 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). While the strategies pursued by these states is groundbreaking, if disparate versions of these regulatory issues emerge (across distinct states), AV manufacturers will incur delays and increased production and testing costs.

Customarily, 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 states that "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" (State of Montana 2011). Smith (2012, p. 95) argues that current law probably does not prohibit automated vehicles, even in states without explicit licensing, though failure to clarify regulations may "discourage their introduction or complicate their operation."

Litigation and Liability

A vehicle driven by a computer on public roads opens the possibility of many insurance and liability issues. Even with near-perfect automated driving, there may be instances in which 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 the object 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 informed decisions. Such decisions may be questioned in court, even if the AV is technically not "at fault".

If AVs are held to a much higher standard that human drivers, 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 (CIS 2013) requires 30 seconds of sensor data storage prior to a collision to help establish fault, assuming that the AV has been programmed and tested properly. Related technologies like parking assist and adaptive cruise control may provide test cases to guide how fully autonomous technologies will be held liable.

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, the problem can be viewed from an effort-and-impact perspective, recognizing the mitigation techniques used in comparable critical infrastructure systems of national importance. According to Jason Hickey (2012), vice president of software security firm Vínsula, current cyber-attacks are more commonly acts of espionage (gaining unauthorized system access for information) rather than sabotage (compromising a system's operation). Disrupting a vehicle's communication or sensors, for example, would require a more complex and sophisticated attack than simply gathering information, and disrupting the 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 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 cybersecurity, 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 were developed with security implemented in the initial development phase (NHTSA 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 difficult (Grau 2012 and Hickey 2012). Though Grau (2012) and Hickey (2012) acknowledge that there is no "silver bullet", such measures make attacks more difficult while limiting potential damage.

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 will likely grow, as AVs and non-autonomous connected vehicles become mainstream and data sharing becomes commonplace. Four primary data-related questions arise: what type of data will be shared, with whom will it be shared, in what way will the data be made available, and for what ends will it be used?

Crash data will likely be available to AV technology suppliers, since they will likely be liable in the event of an AV-caused crash. If a human is driving a vehicle with autonomous capabilities when the crash occurs, however, privacy concerns arise. Few people want their own vehicle's data recorder being used against them in court, though this merely extends an existing issue: 80% of vehicles sold in the U.S. today have similar (but less detailed) event data recorders that describe vehicle actions taken up to five seconds prior to a crash (*The Economist* 2012).

Providing AV travel data including routes, destinations, and departure times to centralized and governmentally controlled systems is likely more controversial, particularly if the data is recorded and stored. Without safeguards, this data could be misused by government employees for stalking 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, like targeted advertising.

At the same time, responsible dissemination and use of AV data can help transportation network managers and designers. Data help facilitate a shift from a gas-tax to a vehicle-miles traveled (VMT) fee, or potentially implement congestion pricing schemes by location and time of day. Those who program traffic signals, for example, could use such data to improve efficiency and reduce delays. In contrast, continuously connected AVs or connected conventional vehicles could illuminate vehicle paths and speed changes, and inform signal systems in real time. Likewise this data could be used to assist planners evaluating future improvements, facilitating more effective investment decision-making. Law enforcement could also benefit, and commercial advertising profits may drive down prices. Any decisions to enhance traveler privacy ideally should be balanced against the benefits of shared data.

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 impact outcomes, creating 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) make clear, AVs will be driving on our streets within the next decade, but it is uncertain when they will comprise a substantial share of the U.S. fleet. Market penetration estimates could 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 include predicting how travel demand patterns will change, how intersections can best be managed (as initially examined by Dresner and Stone [2008]), and how VMT and vehicle emissions will change. With all such estimates in hand, regional planners can incorporate many AV impacts in their travel demand models, traffic delay forecasts, air quality estimates, and related decision-making processes.

POLICY RECOMMENDATIONS

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

1. Expand Autonomous Vehicle Research

Car manufacturers have poured resources into AV technology research and development. Meanwhile research into the impacts that these vehicles could deliver to the transportation system is relatively scarce. This paper has identified key missing links in AV research, including:

- Future AV market penetration rates;
- Travel and land use pattern evolution in the face of AV car-sharing and ride sharing options;
- Emissions and energy impacts of AV operations; and
- Integrated AV and ITS infrastructure investigations, including facilitation of mileage based user fees.

Other gaps will become apparent in coming year and as AVs enter the marketplace. It becomes imperative that agencies around the world and at the federal, state and local level, as well as other stakeholders help fund such research to enable regions and nations to anticipate, and more effectively plan for AV opportunities and impacts.

2. Develop Federal Guidelines for Autonomous Vehicle Licensing

To facilitate regulatory consistency, the U.S. DOT should develop a framework and set of national guidelines for AV licensing at the state level. With a more uniform set of standards in place, states can pool efforts developing safety, operational, and other requirements. AV manufacturers will be better able to meet detailed national requirements, rather than matching 50 potentially different certification regimes across states. Existing state licensing can provide guidance for such efforts, which will streamline AV licensing and testing. Moreover, AV licensing consistencies could help limit AV product liability, as argued by Kalra et al. (2009).

3. Determine Appropriate Standards for Liability, Security, and Data Privacy

Liability, security, and privacy concerns represent substantial barriers to widespread AV technology implementation. These issues should be addressed to give manufactures and investors more certainty in development. Liability standards should strike the balance between assigning responsibility to manufacturers without putting undue pressure on their product. Robust cyber security standards will help the industry develop ways to prevent outside attacks.

AV technology consumers will likely have concerns about use and potential abuse of data collected from their personal travel. Therefore, AV-enabling legislation should balance legitimate privacy concerns against potential data use benefits. Since vehicles will inevitably cross state boundaries, federal regulation should establish parameters for what types of AV data to share, with whom it should be shared, how 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.

CONCLUSIONS

Driverless cars may seem a distant possibility. In reality, autonomous technology is improving quickly, as some automated features are already on current models. This new technology should reduce crashes, ease congestion, improve fuel economy, reduce parking needs, bring mobility to those unable to drive, and eventually revolutionize travel. Based on current research, annual U.S. economic benefits could be around $25 billion with only 10% market penetration. When including broader benefits and high penetration rates, AVs may save the U.S. economy roughly $430 billion annually. While this does not include some associated costs and externalities, the potential for dramatic change to the nature of transportation is very possible.

While potential benefits are substantial, significant implementation and mass-market penetration barriers remain. Initial AV technology costs will likely be unaffordable for most households. States are currently pursuing their own licensing and testing requirements, which may bring a patchwork of regulations and requirements without federal guidance. An AV liability framework 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. Car manufacturers have shown interest in AVs by investing millions of dollars to make self-driving cars. The government should begin focusing research into how AVs could impact transportation and land use patterns, and how to best alter our transportation system to maximize their benefits while anticipating and mitigating negative impacts.

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