Preparing a Nation for Autonomous Vehicles

Opportunities, Barriers and Policy Recommendations

Eno Center for Transportation

October 2013

William P. Eno Paper

Each spring, the Eno Leadership Development Conference brings a select group of the top graduate students in transportation and related disciplines to the Nation's Capital for an introduction to how transportation policy and programs are formed. During their week in Washington, D.C., the "Eno Fellows" meet with leaders from key transportation constituencies, including the U.S. Department of Transportation and its modal administrations, congressional committees, industry associations, and numerous advocacy groups.

The Eno Fellows are also invited to submit abstracts for the William P. Eno Research Paper, a competitive paper competition. There is no constraint on subject matter, but preference is given to papers that provide well-documented, specific and realistic recommendations for strategies to improve transportation. The goal of the paper is to expose a student to the complex nature of transportation policymaking while contributing to Eno's growing knowledge base. This paper is the second annual William P. Eno Research Paper.

About William P. Eno

William P. Eno
1858 - 1945

William Phelps Eno (1858-1945) was an internationally recognized pioneer in traffic control and regulation. Dubbed the "Father of Traffic Safety," Mr. Eno developed the first traffic plans for major cities including New York, London, and Paris, and is credited with helping to invent and popularize stop signs, taxi stands, pedestrian safety islands, and other traffic features commonly used throughout the world. His "rules of the road," adopted by New York City in 1909, became the world's first city traffic plan. He also wrote the first-ever manual of police traffic regulations.

Mr. Eno gradually embraced multimodal transportation interests. He developed a plan for subways in New York City long before anyone else seriously considered the concept. He also became interested in maritime activities, supported railroad development, and instigated research in the 1920s on the future impact of aviation.

In 1921, he chartered and endowed the Eno Center for Transportation to attract the thinking of other transportation experts and specialists and to provide a forum for unbiased discussions that would lead to improvements in the movement of people and goods. Mr. Eno died in 1945 at the age of 86. Ironically, he never drove a car during his lifetime. The Father of Traffic Safety, an avid horseback rider, distrusted automobiles.

Acknowledgements

We would like to thank the Eno Center's Paul Lewis for helping manage this process. Paul's expert guidance was critical in directing the paper's focus, providing valuable feedback at key junctures, and connecting us with excellent reviewers.

Additional thanks go to the many of the experts who provided meaningful feedback and responded to detailed questions along the way, including Eno President and CEO Joshua Schank, Steve Dellenback, Jason Hickey, Alan Grau, and Steve Shladover, among many others. An extra special thanks to this paper's final reviewers: Andy Palanisamy, Patrick Son, Dick Mudge, Joseph Sussman, Mort Downey, and Brian Cullinane. These extraordinary professionals provided valuable feedback and raised many insightful questions, leading to a more thoughtful and nuanced final product.

Finally, we wish to thank the University of Texas' Annette Perrone and the wonderful staff at Eno for helping manage the paper's editing process and readying this paper for publication.

Daniel J. Fagnant
2012 Fellow
Eno Center for Transportation

Kara M. Kockelman, Ph.D., P.E.
Professor, and E.P. Schoch Professor in Engineering
Department of Civil, Architectural and
Environmental Engineering
The University of Texas

About Eno

The Eno Center for Transportation is a neutral, non-partisan think-tank that promotes policy innovation and leads professional development in the transportation industry. As part of its mission, Eno seeks continuous improvement in transportation and its public and private leadership in order to increase the system's mobility, safety and sustainability.

The leader in its field for nearly a century, Eno provides government and industry leaders with timely research and a neutral voice on policy issues. Eno's Center for Transportation Policy (CTP) publishes rigorous, objective analyses on the problems facing transportation and provides ideas for and a clear path toward possible solutions. CTP also publishes a monthly transportation newsletter that reaches 2,500 individuals directly plus another 40,000 through the Transportation Research Board. CTP's policy forums bring together industry leaders to discuss pressing issues and hear from top researchers in the field.

Through its professional development programs, the Center for Transportation Leadership (CTL), Eno cultivates creative and visionary leadership by giving public and private transportation leaders the tools and training the need to succeed together. CTL's leadership Development Conference brings the nation's top transportation students to Washington, DC, each year to meet with top practitioners in the field, while other CTL programs give transportation executives the tools they need to be successful as leaders. Since its inception, CTL has instructed over 3,500 transportation professionals.

Eno was founded in 1921 by Williams Phelps Eno (1859-1945), who pioneered the field of traffic management in the United States and Europe. Mr. Eno sought the promote safe mobility by ensuring that traffic control became an accepted role of government and traffic engineering a recognized professional discipline. His "Rules of the Road", adopted by the City of New York in 1909, became the world's first city traffic plan. He also wrote the first-ever manual of police traffic regulations. In 1921 he chartered and endowed the Eno Center for Transportation to attract the thinking of other transportation experts and specialist, and to provide a forum for unbiased discussions that would lead to improvements in the movement of people and goods.

Table of Contents


Google's Autonomous Vehicle. Photo provided by Google.

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 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.[1] 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,[2] federal guidance has not been issued for either fully, or partially, autonomous vehicles beyond testing purposes on public roads.[3]

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.[4] Nissan[5] and Volvo[6] both 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.

As of April 2013, Google's self-driving cars have driven over 435,000 miles on California public roads, and numerous manufacturers have begun testing driverless systems.

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.

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.[7] 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. 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 CityMobile2 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.[8] 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, and Nevada 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.[9] In contrast, California has directed its DMV to provide AV licensing requirements by 2015.[10]

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, and
- 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.

Aside from making automobiles safer, researchers are also developing ways for AV technology to reduce congestion and fuel consumption.

Potential Benefits

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.

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 percent of these fatal crashes involve alcohol, distraction, drug involvement and/or fatigue.* Self-driven vehicles would not fall prey to human failings, suggesting the potential for at least a 40 percent 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 percent of all crashes.[16] 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,[17] with 2.2 million crashes resulting in injury.[18] At $300 billion, the annual economic cost of crashes is three times higher than that of congestion[19] and is highlighted as the number one transportation goal[20] in the nation’s 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.[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 is challenging.[22] For

Table 1: U.S. Crash Motor Vehicle Scope and Selected Human and Environmental Factor Involvement

Total Crashes per year in U.S.[11]	5.5 million
% human cause as primary factor[12]	93%
Economic Costs of U.S. Crashes[13]	$300 billion
% of U.S. GDP[14]	2%
Total Fatal & Inurious Crashes per Year in U.S.	2.22 million
Fatal Crashes per Year in U.S.[15]	32,367
% of fatal crashes involving alcohol	31%
% involving speeding	30%
% involving distracted driver	21%
% involving failure to keep in proper lane	14%
% involving failure to yield right-of-way	11%
% involving wet road surface	11%
% involving erratic vehicle operation	9%
% involving inexperience or overcorrecting	8%
% involving drugs	7%
% involving ice, snow, debris, or other slippery surface	3.7%
% involving fatigued or sleeping driver	2.5%
% involving other prohibited driver errors (e.g. improper following, driving on shoulder, wrong side of road, improper turn, improper passing, etc.)	21%

example, recognition of humans and other objects in the roadway is both critical and more difficult for AVs than human drivers.[23] 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 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 to implementation.

Ultimately, researchers predict that AVs will overcome many of the obstacles that inhibit them from accurately responding in complex environments. Hayes[24] suggests that motor-vehicle fatality rates (per person-mile traveled) could eventually approach those seen in aviation and rail, about 1 percent of current rates; and KPMG and CAR[25] 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.

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 headways, 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.

---

* 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 percent.

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.

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. But significant congestion reduction could occur if the safety benefits alone are realized. FHWA estimates that 25 percent of congestion is attributable to traffic incidents, around half of which are crashes.[26]

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 percent to 39 percent and 8 percent to 13 percent, respectively, for all vehicles in the freeway travel stream, depending on V2V communication and how traffic-smoothing algorithms are implemented.[27]

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.[28] Shladover et al. estimate that cooperative adaptive cruise control (CACC) deployed at 10 percent, 50 percent, and 90 percent market-penetration levels will increase lanes' effective capacities by around 1 percent, 21 percent and 80 percent, respectively.[29] Headway 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 percent or more AV-market penetration may be required, leaving many years before deployment.[30]

Of course, many such benefits may not be realized until high AV shares are present. For example, if 10 percent 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.[31] 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 headway 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.

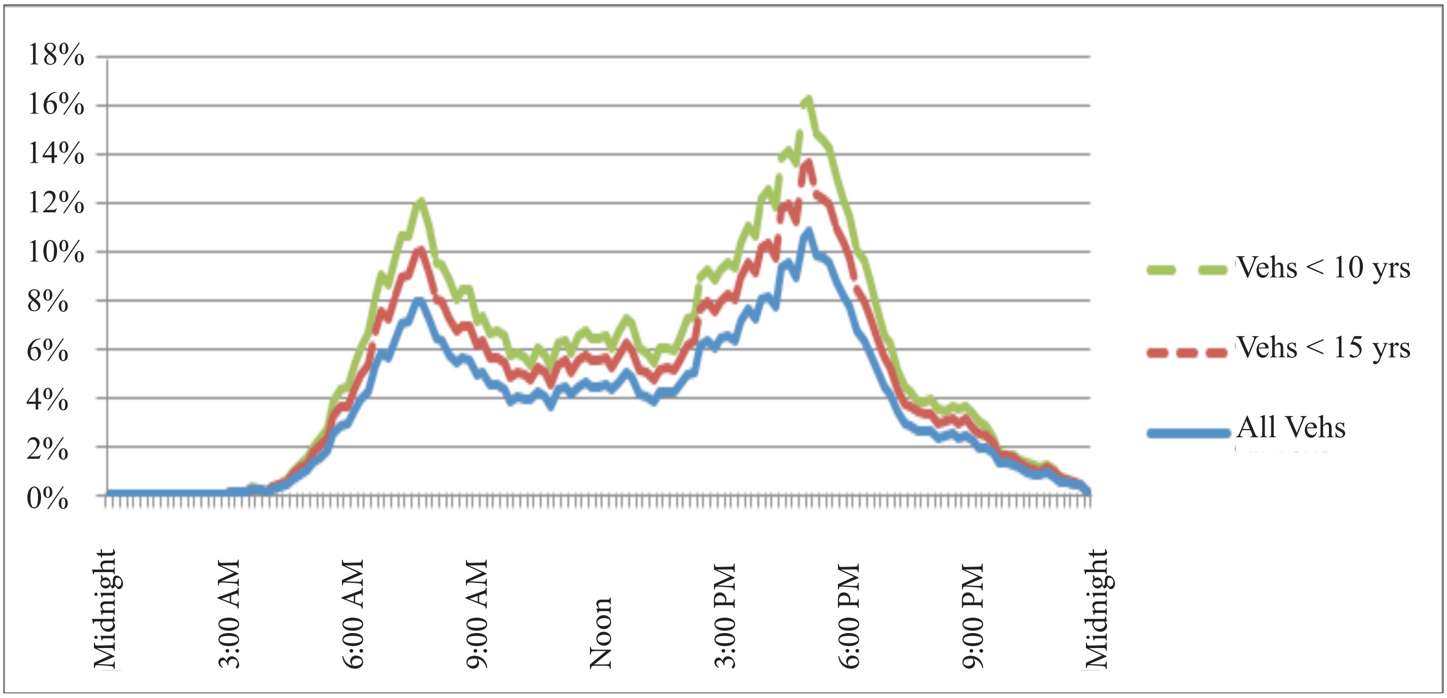


Figure 1: Vehicle Use by Time of Day and by Vehicle Age[43]

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 January 2013, state legislation in California, Florida and Nevada 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 percent faster rate than the nation's overall population.[32] 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.[33] 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.[34] 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 percent yields a reduction in the total number of crashes and their associated injuries and traffic delays by 80 percent. Likewise, unless new travel from AV use is significantly underestimated, research cites that existing infrastructure capacity on highways should be adequate to accommodate the new/induced demand, thanks to AVs' congestion-mitigating features (like traffic smoothing algorithms[35]) and effective capacity-increases (through CACC[36]), as well as public-infrastructure investments (like V2I communication systems with traffics signals[37]) 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. 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[38] estimating that a 20- percent reduction in accelerations and decelerations should lead to 5 percent 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,[39] 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[40] using an agent-based model for assigning vehicles around a region in combination with NHTS data[41] indicate that a single shared AV could replace between nine and thirteen privately owned or household-owned vehicles, without compromising current travel patterns. As shown in Figure 1, even in Seattle where vehicle use is more intense than national averages,[42] just less than 11 percent of vehicles are "in use" throughout the day, even at peak times, though usage rises to 16 percent if only including newer vehicles are monitored.

Freight Transportation

Freight transport on and off the road will also be impacted. The mining company Rio Tinto is already using 10 self-driving ore trucks, with plans to expand to 150 vehicles within four years.[44] 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.


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.

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[45] estimates that four-meter inter-truck spacings could reduce fuel consumption by 10 to 15 percent, and road-train platoons facilitate adaptive braking, potentially enabling further fuel savings. Kunze et al.[46] successfully demonstrated a trial run using 10-meter 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.[47] However, tight vehicle spacing on roads could cause problems for other motorists 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.

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

Table 2: Estimates of Annual Economic Benefits from AVs in the United States

	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	$430	$770	$960
Comprehensive Cost Savings per AV	$1,390	$2,480	$3,100
Congestion Benefits			
Travel Time Savings (M Hours)	756	1680	2772
Fuel Savings (M Gallons)	102	224	724
Total Savings	$16.8 B	$37.4 B	$63.0 B
Savings per AV	$1,320	$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	$2,000	$1,610	$1,670
Annual Savings Per AV: Comprehensive Costs	$2,960	$3,320	$3,900
Net Present Value of AV Benefits minus Added Purchase Price: Economic Costs Only	$5,210	$7,250	$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.	12.7 M	63.7 M	114.7 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	$5,000	$3,000
Discount Rate	10%	10%	10%
Vehicle Lifetime (years)	15	15	15

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 percent, 50 percent and 90 percent. 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. For details on assumption sources and how these estimates were derived, interested readers should see Appendix A. While this analysis is inherently imprecise, it provides an order-of-magnitude estimate of the broad economic and safety impacts this technology may have.

Table 3: AV Owners' Privately Realized Internal Rates of Return (from 0 to 10% Market Share)

Development Stage	**Estimated Added Costs**	**Benefits (Daily Parking & Hourly Value of Travel Time Savings)**							
		\$0 & \$0	**\$0 & \$1**	**\$1 & \$1**	**\$5 & \$1**	**\$1 & \$5**	**\$5 & \$5**	**\$5 & \$10**	**\$10 & \$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%

Table 2 summarizes all of these estimated impacts, suggesting economic benefits reaching \$201 billion (\$447 billion, comprehensive) with a 90 percent 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 percent of benefits and crash savings represent 21 percent of benefits – at the 10 percent market penetration level, versus 33 percent and 58 percent of benefits, respectively, at the 90 percent penetration rate. When comprehensive crash costs are included, overall crash savings jump by more than a factor of three.[❖]

Table 2 illuminates AVs' social benefits, but 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 percent market penetration, taking into account monetary savings from reduced fuel use and insurance, along with several levels of daily parking savings and (hourly) travel time savings. 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-percent rate of return for AV owners.

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[48] 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. 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 percent market penetration, this technology has the potential to save over 1,000 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.

[❖] 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).

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.

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.

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. KPMG and CAR[49] note that the Light Detection and Ranging (LIDAR) systems on top of Google's AVs cost $70,000, and additional costs will accrue from other sensors, software, engineering, and added power and computing requirements. Dellenback[50] 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[51] ranging from $16,000 to $27,000. More cost-effective approaches are possible, with Chengalva et al.[52] paying less than $20K 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[53] 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 10 years. Insurance, fuel, and parking-cost savings may cover much of the added investment. Typical annual ownership and operating costs ranged from $6,000 to $13,000, depending on vehicle model and mileage,[54] with insurance and fuel costs around $900 to $1,000 and $1,100 to $3,700, respectively. These costs may fall by 50 percent for insurance and 13 percent 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[55] found that 37 percent of persons would "definitely" or "probably" purchase a vehicle equipped with autonomous driving capabilities in their next vehicle, though the share dropped to 20 percent after being asked to assume an additional $3,000 purchase price. This is the eventual price increase estimated by Volvo senior engineer Erik Coelingh for AV capabilities,[56] though early-sales' costs will likely be much higher for early adopters, as noted above. Hensley et al.[57] noted that electric vehicle costs have been declining by 6 percent to 8 percent annually, suggesting that it may be 15 years at 8 percent 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 $3,000 mark-up (20 to 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.[58] 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, and eventually just $1,000 to $1,500 more per vehicle.[59] Nevertheless, cost remains high and is therefore a key implementation challenge, due to the current unaffordability of even some of the more basic technologies.

AV Licensing

As of August 2013, California (SB 1298) and Nevada (AB 511) have enacted legislation allowing AV licensing, while Florida's CS/HB 1207 and Washington, D.C.'s B19-0931 have enabled AV testing. Related legislation is pending in Hawaii, Massachusetts, Michigan, Minnesota, New Jersey, New York, South Carolina, Washington, and Wisconsin. States have thus far declined to set many specific restrictions, directing their state DMVs to establish regulatory licensing 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 licensing 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. Finally, California's legislation contains a subsection requiring public hearings on driverless AVs and directs the DMV to enact stricter oversight for such AVs.

As with electric vehicles, technological advances and large-scale production promise greater affordability over time. Dellenback[53] 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 10 years.

While California's DMV rulemaking is expected by 2015, Nevada has already processed AV licenses for Google, Continental, and Audi for testing on Nevada's public roads. These licensing 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

Even with near-perfect autonomous driving, there may be instances where a crash is unavoidable.

speed limits. 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 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[60] 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[61] 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."

Litigation, Liability and Perception

A car or truck driven by a computer on public roads opens up the possibility of many insurance and liability issues. 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 the deer 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[62] 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. 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.

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 Jason Hickey, 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,[64] V2V and V2I protocols have been developed with security implemented in the initial development phase.[65] 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.[66] Though Grau[67] and Hickey[68] 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.

Privacy

California-based consumer education and advocacy organization Consumer Watchdog raised privacy concerns during a recent round of AV-enabling legislation.[69] 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 percent 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 8,500 lbs. by late 2014.[70] 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.[71]

California-based consumer education and advocacy organization Consumer Watchdog raised privacy concerns during a recent round of AV-enabling legislation.

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. 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

If driverless taxis become legal and commercially and technologically viable, they could serve many trips currently served by privately owned vehicles.

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.

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,[72] Google,[73] Nissan [74] and Volvo [75] 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 2013 *Road Vehicle Automation Workshop*,[76] as follows:

- Automated commercial vehicle operations
- Cyber security and resiliency
- Data ownership, access, protection, and discovery
- Energy and environment
- Human factors and human-machine interaction
- Infrastructure and operations
- Liability, risk, and insurance
- Shared mobility and transit
- Testing, certification, and licensing
- V2X communication and architecture

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 automated commercial vehicle operations, energy and environment, infrastructure and operations, and shared mobility and transit focus areas. Furthermore, this list does not make explicit the need for new transportation planning efforts, with most major public investment decisions planned using a 20- to 30-year design horizon. 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.

A strong federal role in funding this research, similar to the federal role in funding numerous technological innovations throughout our nation's history, is essential.

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:

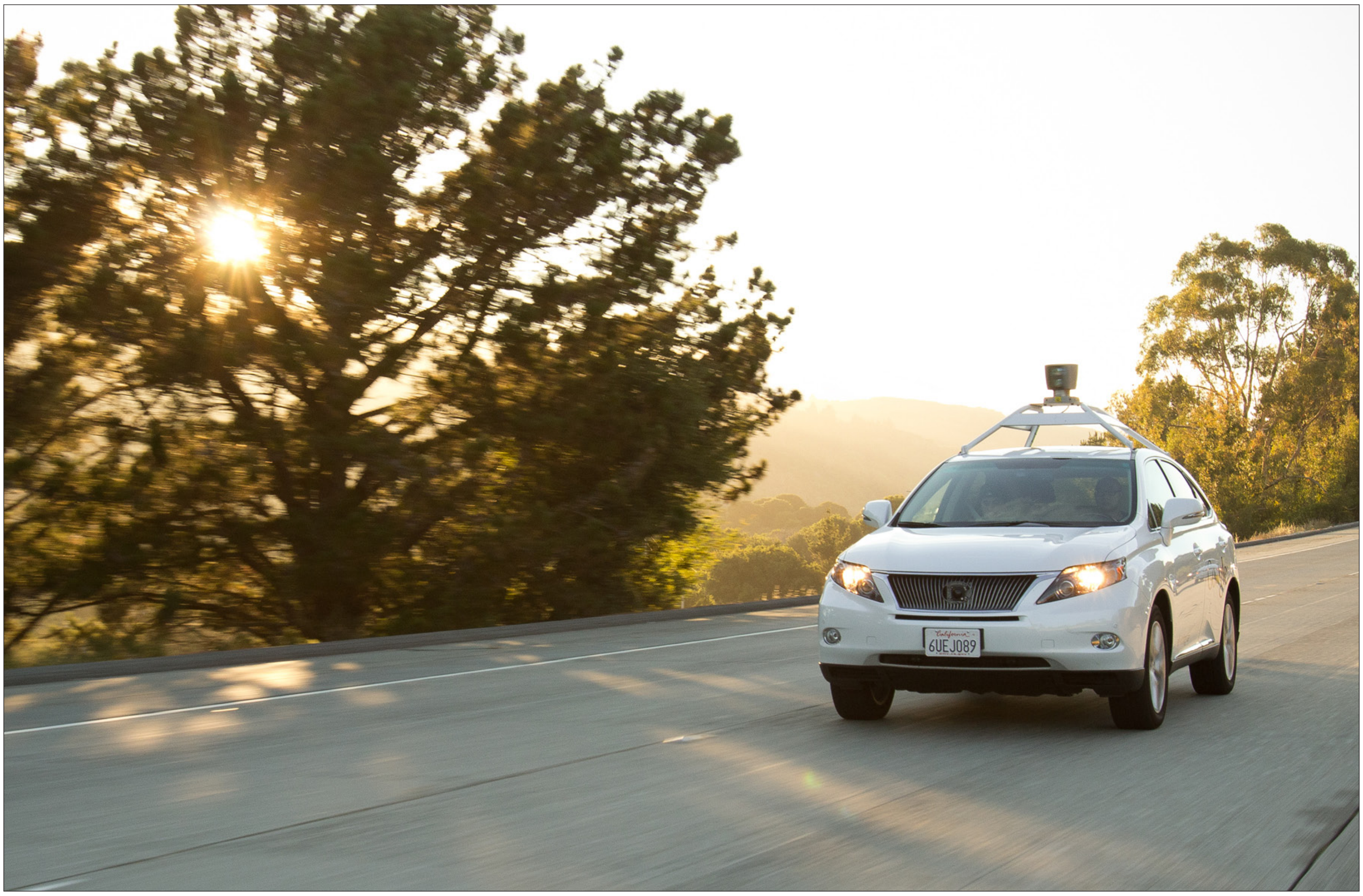
1. Expand Federal Funding for Autonomous Vehicle Research

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 Road-Vehicle Automation Workshop. A strong federal role in funding this research, similar to the 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.

2. Develop Federal Guidelines for Autonomous Vehicle Licensing

To facilitate regulatory consistency, the USDOT should assist in developing a framework and set of national guidelines for AV licensing at the state level. Though NHTSA has developed broad principles for AV testing,[77] licensing AVs for use by the general public is mostly 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[78] *Manual on Uniform Traffic Control Devices* (MUTCD). This approach promotes a single document for adoption by all states, with each state mak-



Car manufacturer Lexus test drives Google's autonomous vehicle. Photo provided by Google.

ing 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 licensing should be seen as a complement to national efforts, which could streamline AV licensing 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 licensing consistencies will likely help limit AV product liability, as argued by Kalra et al.[79]

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 product. 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.

Driverless cars have 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.

Conclusions

The idea of a driverless car may seem a distant possibility, but autonomous technology is improving quickly and some 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 $25 billion with only 10 percent 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 this does not include some of the associated costs and other externalities, 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.

Appendix: Impact Methodology

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.

Changes in VMT

VMT per AV is assumed to be 20 percent higher than that of non-AV vehicles at the 10 percent market penetration rate, and 10 percent higher at the 90 percent market penetration rate. This reflects that early adopters will have more pent-up demand for such vehicles than later buyers. Preliminary agent-based simulations[80] underscore this idea, finding that a fleet of shared AVs serving just 4,100 trips (across a simulated city grid) cover 13 percent of their daily travel unoccupied, with this figure falling to 10 percent as the number of trips served rises to 16,00 (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 review of literature spanning 30 years across California and the U.S., Cervero[81] showed that the long-term (six years or more) urban area elasticity of VMT demand with respect to the number of highway lane-miles supplied ranges from around 0.47 to 1.0, averaging 0.74. This suggests that if a region's lane-miles increase by 1 percent, regional VMT is expected to increase by around 0.74 percent over the long term, after controlling for population, income and other factors.

While the congestion-relieving impact of is similar to that of adding lane-miles, it differs in one crucial respect: AVs' effective capacity expansion is uniform, rather than targeted. Many road segments in a region are not currently congested, and do not have pent-up or elastic demand. This report does not account for induced travel due to latent demand, which may be stemmed if policies like congestion pricing are enacted in concert with the introduction of AVs. However, if a demand elasticity of just 0.37 is applied, system-wide VMT may be expected to rise 26 percent under the 90 percent AV market-penetration assumptions, due to an increase in effective capacity.

Discount Rate and Technology Costs

For net-present-value calculations, a 10 percent discount rate was assumed, which is higher than the 7 percent rate required by the federal Office of Management and Budget (OMB) for federal projects and TIGER grant applications, in order to reflect the greater uncertainty of this emerging technology. Early-introduction costs (five to seven years after initial rollout) at the 10 percent market penetration level were assumed to add $10,000 to the purchase price of a new vehicle, falling to $3,000 by the 90 percent 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, when these are first introduced.

Safety Impacts

The analysis assumes that 10 percent of AVs are shared (at all levels of penetration), and that a single shared AV serves five times as many trips as a non-shared vehicle. 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 percent of the primary factors behind crashes are due to human errors,[83] and 40 percent of fatal crashes involve driver alcohol or drug use, driver distraction and/or fatigue.[84] Therefore, AVs may be assumed to reduce crash and injury rates by 50 percent, versus non-AVs at the early, 10 percent 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 percent safer at the 90 percent market penetration rate (reflecting the near-elimination of human error as a primary crash cause, thanks to greater use of V2V communications and improving AV technologies).

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 percent 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 Coun-

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.

cil[85] guidance, and then on higher comprehensive costs, as recommended by the USDOT,[86] to reflect pain and suffering and the full value of a statistical life.

Congestion Reduction

Shrank and Lomax's congestion impact projections[87] 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 percent 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 percent AV-market penetration level, freeway congestion delays for all vehicles are estimated to fall 15 percent, mostly due to smoothed flow and bottleneck reductions. This is lower than Atiyeh[88] 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 percent market penetration level, a cloud-based system is assumed to be active (Atiyeh[89] suggests 39 percent congestion improvements from smoothed flow), and further capacity enhancements of 20 percent may be realized.[90]

Furthermore, with crashes falling due to safety improvements, another 4.5 percent in congestion reduction may be obtained. Again, induced travel will counteract some of these benefits, and a 35 percent delay reduction on freeways is estimated in this analysis. Finally, at the 90 percent level, freeway congestion is assumed to fall by 60 percent, with the near doubling of roadway capacity and dramatic crash reductions. However, readers should note that capacity [91] and delay are not linearly related and congestion abatement may be even greater than these predictions at the with 90 percent 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), 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 percent at the 10 percent market-penetration level, 10

Moving a parking space outside of the central business districts may save nearly $2,000 in annualized costs.

percent at the 50 percent penetration rate, and 15 percent at 90 percent market penetration. AV fuel efficiency benefits are assumed to begin at 13 percent, increasing to 25 percent with 90 percent 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 percent fuel economy benefits during congested times of day under a 10 percent market penetration, and 13 percent at the 50 percent and 90 percent 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.

Parking

Parking savings comprise the final monetized component of this analysis. Litman[92] 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. So simply moving a parking space outside of the CBD may save nearly $2,000 in annualized costs, while moving one to a suburban location may save another $1,000. 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 percent of AVs being publicly shared).

Privately Realized Benefits

Privately realized benefits were estimated using Table 1's assumptions for the $10,000 purchase price. These were first compared to 50 percent insurance cost savings from a base of $1,000 per year and 13 percent fuel savings from a base of $2,400[93] per year 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.[94] Privately realized internal rates of return were also compared to a higher added-technology price, of $37,500.

End Notes

[1] KPMG and CAR (2012). Self-Driving Cars: The Next Revolution. Ann Arbor, MI.
Economist Technology Quarterly (2012). Inside Story: Look, No Hands. September 1 issue: 17-19.
Grau, Alan (2012). President, Icon Labs. Telephone Interview, October 12.
Hickey, Jason (2012). Vice President, Vínsula. Telephone interview, October 11.

[2] Center for Information and Society (2012). Automated Driving: Legislative and Regulatory Action. Stanford, CA.

[3] National Highway Traffic Safety Administration (2013a). Preliminary Statement of Policy Concerning Automated Vehicles. Washington, D.C.

[4] O'Brien, Chris (2012). Sergey Brin Hopes People will be Driving Google Robot Cars in "Several Years". *Silicon Beat*.

[5] Nissan Motor Company (2013). Nissan Announces Unprecedented Autonomous Drive Benchmarks [Press Release]. http://nissannews.com/en-US/nissan/usa/releases/nissan-announces-unprecedented-autonomous-drive-benchmarks

[6] Carter, Marc (2012). Volvo Developing Accident-Avoiding Self-Driving Cars for the Year 2020. *Inhabitat*. December 5. http://inhabitat.com/volvo-developing-accident-avoiding-self-driving-cars-for-the-year-2020/.

[7] Defense Advanced Research Projects Agency (2012). Grand Challenge '05. Washington, D.C.

[8] *Economist Technology Quarterly* (2012). Inside Story: Look, No Hands. September 1 issue: 17-19.

[9] National Highway Traffic Safety Administration (2013a). Preliminary Statement of Policy Concerning Automated Vehicles. Washington, D.C.

[10] Center for Information and Society (2012). Automated Driving: Legislative and Regulatory Action. Stanford, CA.

[11] Cambridge Systematics (2011). Crashes vs. Congestion: What's the Cost to Society? Prepared for the American Automobile Association.

[12] National Highway Traffic Safety Administration (2008). National Motor Vehicle Crash Causation Survey. U.S. Department of Transportation, Report DOT HS 811 059.

[13] Cambridge Systematics (2011). Crashes vs. Congestion: What's the Cost to Society? Prepared for the American Automobile Association.

[14] Cambridge Systematics (2011). Crashes vs. Congestion: What's the Cost to Society? Prepared for the American Automobile Association.
CIA (2012). *The World Factbook*. U.S. Central Intelligence Agency, Washington D.C. National Highway Traffic Safety Administration (2013b). Traffic Safety Facts. U.S. Department of Transportation, Washington D.C. DOT HS 811 753.

[15] National Highway Traffic Safety Administration (2012a). Fatal Analysis Reporting System. U.S. Department of Transportation, Washington D.C.

[16] National Highway Traffic Safety Administration (2008). National Motor Vehicle Crash Causation Survey. U.S. Department of Transportation, Report DOT HS 811 059.

[17] National Highway Traffic Safety Administration (2012a). Fatal Analysis Reporting System. U.S. Department of Transportation, Washington D.C.

[18] Ibid. 19.

[19] Cambridge Systematics (2011). Crashes vs. Congestion: What's the Cost to Society? Prepared for the American Automobile Association.

[20] U.S. House of Representatives and Senate (2012). MAP-21 Conference Report to Accompany H.R. 4348. Report 112-557.

[21] CDC (2011). Injury Prevention and Control: Data and Statistics. Center for Disease Control. Atlanta, GA.

[22] Campbell, Mark, Magnus Egerstedt, Jonathan How, and Richard Murray (2010). Autonomous Driving in Urban Environments: Approaches, Lessons and Challenges. Philosophical Transactions of the Royal Society.

[23] Dalal, Navneet and Bill Triggs (2005). Histogram of Oriented Gradients for Human Detection. 2005 Computer Society Conference on Computer Vision and Pattern Recognition, IEEE. CVPR (1) 886-893. http://lear.inrialpes.fr/people/triggs/pubs/Dalal-cvpr05.pdf.

Economist Technology Quarterly (2012). Inside Story: Look, No Hands. September 1 issue: 17-19. Farhadi, Ali, Ina Endres, Derek Hoiem, and David Forsyth (2009). Describing Objects by their Attributes. 2009 Computer Society Conference on Computer Vision and Pattern Recognition.

[24] Hayes, Brian (2011). Leave the Driving to it. *American Scientist*. 99: 362-366.

[25] KPMG and CAR (2012). Self-Driving Cars: The Next Revolution. Ann Arbor, MI.

[26] Federal Highway Administration (2005). Traffic Congestion and Reliability: Linking Solutions to Problems. Washington, D.C.

[27] Atiyeh, Clifford (2012). Predicting Traffic Patterns, One Honda at a Time. *MSN Auto*, June 25.

[28] Tientrakool, Patcharinee (2011). Highway Capacity Benefits from Using Vehicle-to-Vehicle Communication and Sensors for Collision Avoidance. Vehicular Technology Conference (VTC Fall) 2011 IEEE. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6093130.

[29] Shladover, Steven, Dongyan Su and Xiao-Yun Lu (2012). Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow. *Proceedings of the 91st Annual Meeting of the Transportation Research Board*. Washington, D.C.

[30] Dresner, Kurt, and Peter Stone (2008). A multiagent approach to autonomous intersection management. *Journal of Artificial Intelligence Research* 31: 591-656.

[31] Bose, Arnab and Petros Ioannou (2003). Analysis of Traffic Flow with Mixed Manual and Semiautomated Vehicles. *IEEE Transactions on Intelligent Transportation Systems*. 4:173-188.

Atiyeh, Clifford (2012). Predicting Traffic Patterns, One Honda at a Time. *MSN Auto*, June 25.

[32] U.S. Census Bureau (2011). Age and Sex Composition: 2010. C2010BR-03.

[33] Wood, Joanne (2002). Aging Driving and Vision. *Clinical and Experimental Optometry*; 85: 214-220.

[34] Kockelman, Kara & Sukumar Kalmanje (2006). Road Pricing Simulations: Traffic, Land Use and Welfare Impacts for Austin, Texas. *Transportation Planning and Technology* 29 (1): 1-23.

[35] Atiyeh, Clifford (2012). Predicting Traffic Patterns, One Honda at a Time. MSN Auto, June 25.

[36] Shladover, Steven, Dongyan Su and Xiao-Yun Lu (2012). Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow. *Proceedings of the 91st Annual Meeting of the Transportation Research Board*. Washington, D.C.

[37] KPMG and CAR (2012). Self-Driving Cars: The Next Revolution. Ann Arbor, MI.

[38] Berry, Irene (2010). The Effects of Driving Style and Vehicle Performance on the Real-World Fuel C onsumption of U.S. Light-Duty Vehicles. Massachusetts Institute of Technology. Cambridge, MA.

[39] Bullis, Kevin (2011). How Vehicle Automation Will Cut Fuel Consumption. MIT's *Technology Review*. October 24. Shoup, Donald (2005). *The High Cost of Free Parking*. APA Planners Press. ISBN 978-1-884829-98-7.

[40] Fagnant, Daniel and Kara Kockelman (2013). Environmental Implications for Autonomous Shared Vehicles Using Agent-Based Model Simulation. Working paper under review in *Transportation Part C*.

[41] Federal Highway Administration (2009b) National Household Travel Survey. U.S. Department of Transportation. Washington, D.C.

[42] KPMG and CAR (2012). Self-Driving Cars: The Next Revolution. Ann Arbor, MI.

Puget Sound Regional Council (2006). 2006 Household Activity Survey. Seattle, WA.

[43] PSRC 2006 household travel survey data

[44] *Economist Technology Quarterly* (2012). Inside Story: Look, No Hands. September 1 issue: 17-19.

[45] Bullis, Kevin (2011). How Vehicle Automation will Cut Fuel Consumption. MIT's *Technology Review*. October 24.

[46] Kunze, Ralph, Richard Ramakers, Klaus Henning and Sabina Jeschke (2009). Organization of Electronically Coupled Truck Platoons on German Motorways. *Intelligent Robotics and Applications: Second International Conference*, Vol. 5928: 135-146.

[47] Newcomb, David (2012). Road-Train Test Keeps Cars in Line. *Wired*. May 29.

[48] Bureau of Labor Statistics (2012). Occupational Outlook Handbook: Transportation and Moving Occupations. Washington, D.C.

[49] KPMG and CAR (2012). Self-Driving Cars: The Next Revolution. Ann Arbor, MI.

[50] Dellenback, Steven (2013). Director, Intelligent Systems Department, Automation and Data Systems Division, Southwest Research Institute. Communication by email, May 26.

[51] Boesler, Matthew (2012). The 27 Best Selling Vehicles in America. *Business Insider*.

[52] Chengalva, Mahesh, Richard Bletsis and Bernard Moss (2009). Low-Cost Autonomous Vehicles for Urban Environments. *SAE International Journal of Commercial Vehicles* 1(1): 516-527.

[53] Dellenback, Steven (2013). Director, Intelligent Systems Department, Automation and Data Systems Division, Southwest Research Institute. Communication by email, May 26.

[54] American Automobile Association (2012). Your Driving Costs: How Much are you Really Paying to Drive? Heathrow, FL.

[55] J.D. Power and Associates (2012). 2012 U.S. Automotive Emerging Technology Study.

[56] *Economist Technology Quarterly* (2012). Inside Story: Look, No Hands. September 1 issue: 17-19.

[57] Hensley, Russel, Stefan Knupfer, and Dickon Pinner (2009). Electrifying Cars: How Three Industries will Evolve. *McKinsey Quarterly*. 3: 87-96.

[58] BMW of North America (2013). Build Your Own 2013 528i Sedan. Woodcliff Lake, NJ.

[59] KPMG and CAR (2012). Self-Driving Cars: The Next Revolution. Ann Arbor, MI.

[60] State of Montana (2011). Montana Code Annotated 2011: 61-5-401. Driver License Compact.

[61] Smith, Bryant Walker (2012). Automated Vehicles are Probably Legal in the United States. *Center for Internet and Society*. Stanford, CA.

[62] Center for Information and Society (2012). Automated Driving: Legislative and Regulatory Action. Stanford, CA.

[63] Hickey, Jason (2012). Vice President, Vínsula. Telephone interview, October 11.

[64] Hickey, Jason (2012). Vice President, Vínsula. Telephone interview, October 11.

[65] Hickey, Jason (2012). Vice President, Vínsula. Telephone interview, October 11.

[66] National Highway Traffic Safety Administration (2011). USDOT Connected Vehicle Research Program: Vehicle-to-Vehicle Safety Application Research Plan. DOT HS 811 373. Grau, Alan (2012). President, Icon Labs. Telephone Interview, October 12.

[67] Grau, Alan (2012). President, Icon Labs. Telephone Interview, October 12.

[68] Hickey, Jason (2012). Vice President, Vínsula. Telephone interview, October 11.

[69] Brandon, John (2012). Privacy Concerns Raised over California "Robot Car" Legislation. *Fox News*, September 14.

[70] National Highway Traffic Safety Administration (2012b). USDOT Proposes Broader Use of Event Data Recorders to Help Improve Vehicle Safety. U.S. Department of Transportation, NHTSA 46-10. Washington, D.C.

[71] Kaste, Martin (2013). Yes, Your New Car has a 'Black Box.' Where's the Off Switch? National Public Radio. March 20.

[72] KPMG and CAR (2012). Self-Driving Cars: The Next Revolution. Ann Arbor, MI.

[73] O'Brien, Chris (2012). Sergey Brin Hopes People will be Driving Google Robot Cars in "Several Years". *Silicon Beat*.

[74] Nissan Motor Company (2013). Nissan Announces Unprecedented Autonomous Drive Benchmarks [Press Release]. http://nissannews.com/en-US/nissan/usa/releases/nissan-announces-unprecedented-autonomous-drive-benchmarks.

[75] Carter, Marc (2012). Volvo Developing Accident-Avoiding Self-Driving Cars for the Year 2020. *Inhabitat*. December 5. http://inhabitat.com/volvo-developing-accident-avoiding-self-driving-cars-for-the-year-2020/.

[76] KPMG and CAR (2012). Self-Driving Cars: The Next Revolution. Ann Arbor, MI.

[77] National Highway Traffic Safety Administration (2013a). Preliminary Statement of Policy Concerning Automated Vehicles. Washington, D.C.

[78] Federal Highway Administration (2009a). Manual on Uniform Traffic Control Devices. U.S. Department of Transportation. Washington, D.C. http://mutcd.fhwa.dot.gov/.

[79] Kalra, Nidhi, James Anderson and Martin Wachs (2009). Liability and Regulation of Autonomous Vehicle Technologies. California PATH Research Report UCB-ITS-PRR-2009-28.

[80] Fagnant, Daniel and Kara Kockelman (2013). Environmental Implications for Autonomous Shared Vehicles Using Agent-Based Model Simulation. Working paper under review in *Transportation Part C*.

[81] Cervero, Robert (2001). Induced Demand: An Urban and Metropolitan Perspective. Prepared for Policy Forum: Working Together to Address Induced Demand. Berkeley, CA.

[82] LaHood, Ray (2011). Notice of Funding Availability for the Department of Transportation's National Infrastructure Investments Under the Full-Year Continuing Appropriations. U.S. Department of Transportation. Federal Register 76 (156): 50310.

[83] National Highway Traffic Safety Administration (2008). National Motor Vehicle Crash Causation Survey. U.S. Department of Transportation, Report DOT HS 811 059.

[84] National Highway Traffic Safety Administration (2012a). Fatal Analysis Reporting System. U.S. Department of Transportation, Washington D.C.

[85] National Safety Council (2012). Estimating the Costs of Unintentional Injuries. Washington, D.C.

[86] Trottenberg, Polly (2011). Treatment of the Value of Preventing Fatalities and Injuries in Preparing Economic Analysis – 2011 Revision. U.S. Department of Transportation, Washington, D.C.

[87] Schrank, David and Tim Lomax (2011). 2011 Urban Mobility Report. Texas Transportation Institute. College Station, TX.

[88] Atiyeh, Clifford (2012). Predicting Traffic Patterns, One Honda at a Time. *MSN Auto*, June 25.

[89] Atiyeh, Clifford (2012). Predicting Traffic Patterns, One Honda at a Time. *MSN Auto*, June 25.

[90] Shladover, Steven, Dongyan Su and Xiao-Yun Lu (2012). Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow. *Proceedings of the 91st Annual Meeting of the Transportation Research Board*. Washington, D.C.

[91] Shladover, Steven, Dongyan Su and Xiao-Yun Lu (2012). Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow. *Proceedings of the 91st Annual Meeting of the Transportation Research Board*. Washington, D.C.

[92] Litman, Todd (2012). Parking Management: Strategies, Evaluation and Planning. Victoria Transport Policy Institute. Victoria, B.C.

[93] American Automobile Association (2012). Your Driving Costs: How Much are you Really Paying to Drive? Heathrow, FL.

[94] Federal Highway Administration (2013). Public Data for Highway Statistics. Office of Highway Policy Information. Washington, D.C.

Staff

Eno Center for Transportation Staff

Daniel J. Fagnant
2012 Fellow
Eno Center for Transportation

Joshua Schank
President and CEO
Eno Center for Transportation

Paul Lewis
Policy and Strategic Finance Analyst
Eno Center for Transportation

Pamela Shepherd
Senior Director of Communications
Eno Center for Transportation

Eno Board of Directors

Lillian C. Borrone
Chairman
Eno Center for Transportation

Michael T. Burns
General Manager
Santa Clara Valley
Transportation Authority

Maria Cino
Vice President, Government Relations
Hewlett-Packard

Mortimer L. Downey
Senior Advisor
Parsons Brinckerhoff

Norman Y. Mineta
Principal
Mineta LLC

Eugene K. Pentimonti
Maersk (retired)

David Z. Plavin
President
dzp Consult, Inc.

Jerry Premo
Executive Vice President
AECOM

Phillip A. Washington
General Manager
Regional Transportation District

Martin T. Whitmer, Jr.
Principal
Whitmer & Worrall

Tay Yoshitani
Chief Executive Officer
Port of Seattle

Eno
Center for
Transportation

Eno Center for Transportation
1710 Rhode Island Avenue, NW, Suite 500
Washington, DC 20036
www.enotrans.org