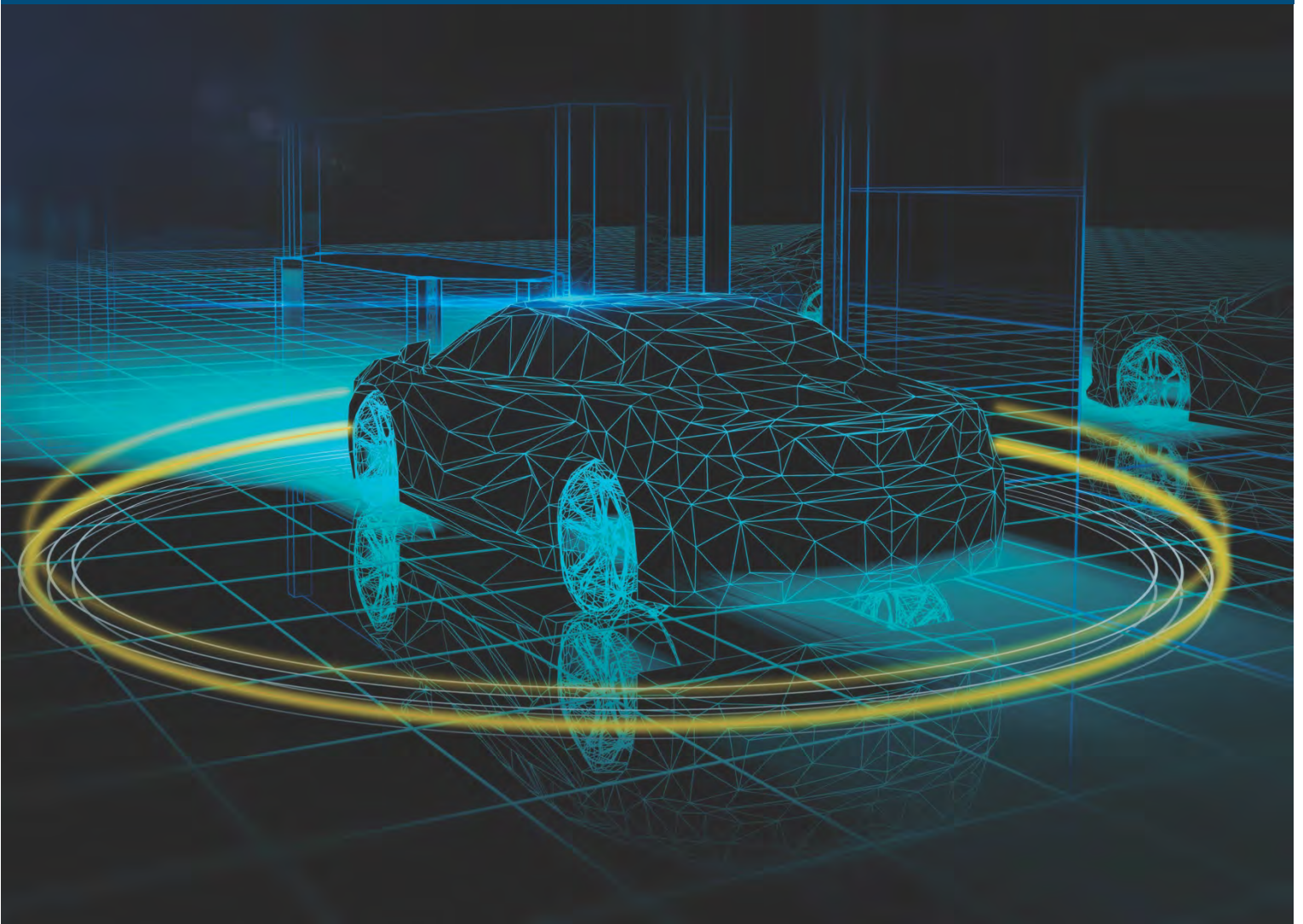


Market Framework and Outlook for Automated Vehicle Systems





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CONTENTS

Executive Summary	iv
Framing Automated and Autonomous Systems.....	iv
Summary Conclusions About the Market Today	v
Trigger Points.....	vi
Next Steps.....	viii
1. Overview of This Study	9
“Vehicle” Defined	9
2. Market Context.....	11
Background.....	11
Outlook for Factors That Influence Technology Adoption.....	13
DSRC versus 5G.....	14
3. A Market-Based Automated Systems Framework	15
Safe Systems	17
Self-Driving Systems	17
Driverless Systems.....	19
4. History and Outlook for Advanced/Automated Vehicle Systems	21
Striving for Standardization	21
NHTSA’s Five Eras of Safety	24
Vehicle Technology Introduction Mapped to Automation Classes	25
Phases of Automated/Autonomous Vehicle Introduction and Impacts	28
Outlook for Safety Improvements.....	31
5. Institutional Issues	34
6. Trigger Points.....	37
Institutional/Regulatory	37
Technology	40
Vehicles.....	41
7. Conclusions.....	42
Appendix A.....	1
Cross-reference to Other Classification Schemes	1
Endnotes.....	3

Executive Summary

The surface transportation industry is in the early stages of profound changes, which have been stimulated by the development of increasingly sophisticated driving safety and automation technologies. While each of these technologies represents important advances in its own right, when fused with new automated driving algorithms, they open the door for a new era:

1. Mobility as a service using driverless vehicles
2. A shift from a world where most vehicles are privately owned to one where most personal travel might be in shared fleet-owned/operated vehicles
3. A shift in institutional leadership away from state and local departments of transportation toward private service providers and regulatory agencies.

Each of these changes has important implications for risks that actuaries are asked to assess.

Considerable uncertainty exists regarding the speed with which these changes will take place and the nature of their impact on safety, the overall demand for travel, vehicle sales and vehicle ownership. This report does not attempt to forecast the pace of these changes; instead it advances a list of “trigger points” that may serve as leading indicators of change.

Framing Automated and Autonomous Systems

The automated and autonomous vehicle (AV) industry is characterized by a large array of often overlapping technical jargon. Terms describe individual technologies as well as different levels of automation. This report distills these terms to focus on three market-related definitions:

- **Safe.** The driver is solely responsible for the driving task, but technology in the vehicle can improve safety by alerting the driver to risks or simply overriding driver action so as to avoid lane departures and/or crashes. These technologies are widely available in a range of levels from minimal crash mitigation to effective crash avoidance. They are being offered in an increasing share of new vehicles. The retrofit market for used cars does not yet exist.
- **Self.** These cars can assume responsibility for select driving tasks under specific road or weather conditions. They require an alert driver who is ready to take control under conditions the technology cannot handle. Self-driving technologies are currently emerging. Because their performance depends on driver intervention, their safety benefits beyond Safe technologies are not yet well understood, but their safety impacts are not expected to be substantially better than the best Safe systems. The industry will need to work hard to avoid them being worse.
- **Driverless.** These vehicles are responsible for all driving tasks. No driver is required during the trip. In the near term, their operation will be limited to defined locations during favorable weather conditions. These vehicles are still under development, although the technology has been implemented for certain low-speed vehicles. Waymo’s deployment in Phoenix, Arizona, in early 2018 was the first public test of unattended driverless vehicles for un demand shared rides

within a designated street network. Waymo (using a new name) plans to begin commercial on-demand service in December, 2018.

- Safe and Driverless are most relevant for the insurance industry since they 1) are likely to have the largest overall impact on vehicle safety and 2) they frame the range of changes that will affect the insurance industry.

Summary Conclusions About the Market Today

Despite uncertainty about the specific timetable for deployment of these technologies and their likely impacts on safety, travel demand, and vehicle ownership, two broad conclusions are evident:

1. Advanced vehicle automation is coming soon—sooner than those outside the industry generally expect.
2. The impact of these changes will be unprecedented. They will affect every aspect of the motor vehicle industry (266 million vehicles in the United States alone), including all vehicle insurance (directly through changes in vehicle safety, performance and ownership, and indirectly through total trips, mix of trip types, intensity of use, total number of vehicles required to meet demand, and relative share of occupied/unoccupied vehicle miles traveled); infrastructure insurance (transit, highways); and even residential insurance. They will also generate shifts in where people live and work and in the overall structure of the economy.

Based on recent events and trends, it is also possible to suggest some likely outcomes within the industry:

- Safety will improve quickly but incrementally. The Safe class of vehicles is already being deployed and will generate important safety gains. Driverless vehicles will help, but important gains in safety will nonetheless occur before Driverless vehicles arrive in large numbers.
- State and federal regulatory agencies have been helpful with policies and regulations that allow innovation. While federal legislation is stalled, the U.S. Department of Transportation recently released new guidance for the design, testing and deployment of automated vehicles in “Preparing for the Future of Transportation: Automated Vehicles 3.0.”¹ This guidance continues the current policy of not picking “winners or losers” and relying on self-regulation (as with nonautomated vehicles).
- Early driverless deployments will appear in specific domains (good weather, defined locations, medium-density regions and so on), rather than broadly, but they may expand quickly.
- Vehicle-to-vehicle and infrastructure communication will migrate away from a public-sector specification, relying instead on commercial solutions that can likewise capitalize on new communications systems developments, such as 5G networks.

- Data ownership issues will grow in importance—an issue that has already become apparent in the wake of recent automated system crash investigations.
- Fleet ownership and operation will be a major part of driverless vehicle deployment, in part due to higher vehicle costs and in part due to strong private sector returns and professional oversight and maintenance of more complex vehicles.
- Cybersecurity will become a substantial technical concern.
- As per mile costs decrease, travel will increase. This will be true for passengers (particularly as part of shared rides in individual vehicles) but also for vehicle miles traveled since the ability to carry out other activities while traveling will provide incentives for longer commutes or for vehicle travel rather than short-haul airlines.

Trigger Points

Table 1 presents a list of changes in policy, technology or vehicles that could affect the pace of adoption and deployment for Safe, Self and Driverless vehicles. Importantly, these trigger points are not forecasts or projections, but events with implications for development of the autonomous vehicle industry. Scenarios in which the implications of realizing one or more are explored.

Table 1
TRIGGER POINTS THAT AFFECT THE ADOPTION AND MARKET PENETRATION OF AUTOMATED AND AUTONOMOUS VEHICLES

Trigger	Possible Impacts
POLICY	
Promulgation of regulatory requirement for a specific technology	Although it is likely to speed deployment, the requirement may also encourage firms to slow deployment as they wait for action by NHTSA. There are risks of restrictive regulations by local governments.
Clarification of state versus federal regulatory responsibilities	Inconsistent regulations among states may add to vehicle costs. Federal legislation could help, but there is a risk of too much detail too early.
Requirement for technology information in vehicle identification number	This would encourage deployment and support analysis of technology effectiveness.
TECHNOLOGY	
Automated emergency braking	Increased standardization and measurement of effectiveness could improve safety and speed up driverless solutions.
Rapidly falling cost of lidar systems (e.g., below \$500 per unit)	Lidar units are key to effective self-driving and driverless systems, so lower costs would accelerate the deployment of vehicles equipped with these systems, possibly also supporting vehicle retrofits.
Costs and effectiveness of other sensors	As with lidar, this would accelerate the deployment of self-driving and driverless vehicles. No industry standards currently exist.
Growth in vehicle cybersecurity insurance (reduced cyber risks)	Cybersecurity is a major risk for deployment, and the problem is not unique to automated vehicles.
VEHICLES AND VEHICLE USE	
Tracking percentage of privately owned light vehicles and commercial light vehicles equipped for Safe or Self	Share of personally owned vehicles with Safe and Self-Driving systems should be tracked, ideally by technology.
Increased ridesharing, measured as an increase in average vehicle occupancy	Widespread ridesharing would indicate the likely use of shared autonomous vehicles.
Growth of Driverless vehicle market share of vehicle miles traveled (VMT) or passenger miles traveled (PMT) <i>in a given market</i> to greater than 1%, 5%, 10% and so on (Detail by region is important.)	Ten percent market share is often viewed as key to generating noticeable gains in safety and roadway capacity for interstate-level roads.
Growth of the percentage of interstate Driverless truck VMT to greater than 1% or higher (Detail by region is important.)	Detail should cover both partial and full automation (driverless).

Next Steps

The findings of this and many other studies in the industry point to the need to actively track and assess industry developments. Possible next steps therefore include the following:

- Developing more and better data regarding the impact of different technologies on safety. Timely distribution of results is important. The Insurance Institute for Highway Safety (IIHS) is a key source of this information, which should include:
 - Interactions among individual technologies
 - Variation in the performance of installed technologies among different manufacturer models, supported by sample sizes that allow for more confident generalization of findings
- Integrating research and findings with NHTSA's research and regulatory work.
- Tracking and regularly reporting on trigger points to anticipate change in the pace of deployment and likely impacts on the use of vehicles.

Ultimately, the industry should also work with the Society of Actuaries and insurance companies to focus research, speed the collection and dissemination of data regarding the safety impacts of different technologies, and support federal and state regulatory processes.

1. Overview of This Study

This study examines the nature of the rapidly evolving market for advanced and autonomous vehicles. In describing the current status and possible future development of vehicle technology, it draws on existing research, expert opinion and updates from industry symposia. The goal is to classify the major technologies and their pace of development and thereby understand the market direction and possible implications for vehicle safety. While the general direction of the industry is clear, no reliable forecasts exist regarding the pace of change or market penetration for automated and autonomous vehicles. Consequently, this report advances a set of trigger points to explain key factors that are likely to influence the pace of change and possible implications for the transportation industry, for safety and for vehicle insurance.

This report:

- Presents a new framework for classifying automated vehicle systems relevant to commercial interests, including the insurance industry;
- Summarizes the history and outlook for safety systems and automation;
- Examines institutional issues that will influence how vehicle technology is deployed and used;
- Defines trigger points—events that can materially change the market development for automated and autonomous vehicles; and
- Concludes by summarizing findings and possible next steps for the industry.

“Vehicle” Defined

Advanced driver assistance and/or autonomous operating technology spans road, rail, air and water transport. There is no single type of autonomous vehicle. For this study, the term *vehicle* comprises road-based vehicles, including:

- Light-duty vehicles, such as
 - **Private vehicles**, perhaps the most widely reported dimension of automation, with leaders in autonomy including Audi, Tesla, Volvo, BMW and GM (as well as several Chinese companies). This also includes new vehicle types, such as smaller vehicles for urban travel, that have yet to enter the market.
 - **Autonomous low-speed shuttles**, including active, early stage deployments in Greenville, South Carolina (Robotic Research with Local Motors); Las Vegas, Nevada (Navya); Babcock Ranch, Florida (EasyMile); and Bishop Ranch, California (EasyMile). About 10 firms are active in this market.
 - **Shared vehicles** for use as automated taxis, variously referred to as “A-Taxis,” “mobility as a service” and “transportation as a service.” Leaders include Waymo (part of Google), Uber, and Lyft as well as some original equipment manufacturers (OEMs) that are in the early stages in this market, such as GM’s Cruise division and Volvo. Partnerships

between technology firms and auto OEMs have begun, such as Waymo with Chrysler and Jaguar, Honda with Cruise, and Uber with Volvo. Some additional firms, such as Zook and Apple, have products that are still in development and have yet to enter the market.

- City buses, still largely being adapted to new sensor technology to improve safety, but with manufacturers and operators actively investigating partial or fully autonomous operations. A growing number of transit authorities have begun to deploy sensors that help to identify pedestrians and vehicles, motivated in large part by the ability to reduce insurance costs.
- Trucks, including local and long-haul trucks, with the latter category the first target of autonomous systems developers and fleet platooning (for improved fuel efficiency). Leading developers of autonomous systems include Embark; Starsky Robotics; Navistar (with support from partner Volkswagen Truck & Bus GmbH); Tesla (with an all-electric truck); and Waymo. Local or urban freight movement involves a mix of vehicle types, including small “sidewalk” units and drones.

This study does not consider applications in aviation, shipping, or ground-based “bots”/carts for light goods distribution (envisioned both within warehouses/distribution centers and for city streets).

Most major manufacturers have already integrated safety technology into light-duty vehicles and are now turning to self-driving and driverless technologies. In trucking, a subset of manufacturers is integrating proven technologies and beginning to explore advanced, emerging systems, such as platooning and autonomous operation. *

* Peloton is focused on a particular aspect of the automation market, vehicle platoons, with a driver in each truck and all trucks operating in close proximity to one another while on the highway for reduced drag and improved fuel economy.

2. Market Context

Background

Transportation is experiencing a series of dramatic changes driven by rapid advances in vehicle technology, new institutions and the growth of shared mobility. These changes, in turn, have created both anticipation regarding the benefits of this new world and uncertainty about when they would occur and their likely impacts (positive and negative).

One force behind this change has been significant investment by the private sector, including firms that have never been involved in vehicle manufacturing or transportation services. The Brookings Institution estimates private-sector investment in autonomous vehicle technologies over the past five years at \$80 billion.²

One motivation for this investment has been a sea change in the economic value of transportation. Rather than a focus on the value of new vehicles sold every year, the emphasis is now on the value of the travel itself. The value of miles traveled has been estimated at \$10 trillion annually versus just \$1.5 trillion annually for the vehicles in which we travel.³ The average private car is only used about 4% of the time. Some believe that a switch to shared mobility could reduce the cost of travel from \$0.76–\$1.00 per mile today for a private vehicle to \$0.20–\$0.45 per mile—with even more dramatic reductions for a shared vehicle.⁴ If correct, this reduction in cost is guaranteed to stimulate a huge growth in travel. The potential size of this market is one reason for the burst of private investment and activity by technology firms, including many with no previous involvement with vehicles.

Fueling this anticipation is an extraordinary amount of press coverage. Unfortunately, much of this coverage clouds the underlying reality of what specific technology works today, what is expected to work in the foreseeable future, what the likely impacts may be on society and the economy, and when we can expect breakthroughs leading to true driverless capabilities.

Further complicating industry understanding is the fact that neither the press nor the industry has used consistent nomenclature, often using different terms to explain the same concept or capability, such as using *autonomous* and *self-driving* (or even *fully self-driving*) interchangeably. In the interest of improving precision and consistency—and to make a distinction in capabilities inherently important to the insurance industry—this study categorizes truly autonomous vehicle systems as Driverless and those that still require an alert driver ready to take control as Self-driving.*

The fact that autonomous vehicles have now safely driven millions of miles in testing and that major manufacturers plan to sell such vehicles or make them available to travelers in the near future raises high expectations. To a certain degree, these predictions are being realized—in certain cases, much sooner than anticipated even just one year ago.

* These terms, their specific definitions and their alignment with other classification systems is discussed in detail later in this report.

Of course, because we are in the midst of the development cycle, manufacturer's plans often change. In December 2017, for example, Volvo changed its plans to launch autonomous vehicles by 2018, announcing a new target of 2021, and then with only self-driving capabilities.⁵ Yet the fact remains that we are in the midst of deployment. Therefore, while there is good reason to be cautious when projecting what technologies will appear and when, certain elements are undeniable:

- Many important underlying technologies are already in the marketplace today.
- Most technologies viewed as key for autonomous vehicles will reach the market within the next three years.
- Autonomous vehicles are expected to appear in limited numbers* within the next two to three years, and specialized autonomous applications, such as low-speed shuttles for individual neighborhoods, have already begun to be deployed.
- Advanced and autonomous technologies are expected to mature and become broadly available within the next 10 years.

Together, these technologies will lead to the most disruptive change in transportation since the advent of the automobile itself. Some technological advances and impacts are relatively foreseeable—primarily those for which there is historical precedent, such as technologies that advance safety without changing the relationship between the manufacturer, suppliers, distributors, insurers, government and owner/operators.

Much more is without precedent. Driverless vehicles hold the potential to change many of the established historical institutional and commercial relationships simultaneously and affect many outside of the established boundaries, including land use, transit, parking, congestion, environmental issues and even alcohol use.⁶ Consequently, unlike a change to an existing capability, such as the introduction of antilock brakes, there is no historical record of performance that provides a guide when considering the impact of certain new safety technologies or of driverless systems, generally.[†]

In spite of the uncertainty regarding impact and timing, two conclusions are evident:

1. Advanced vehicle automation is coming soon. Estimates of deployment completed within the last two years already require updates.
2. The impact of these changes will be unprecedented. They will affect every aspect of the motor vehicle industry (266 million vehicles in the United States alone),⁷ including all vehicle insurance (directly through changes in vehicle safety, performance and ownership, and indirectly through total trips, mix of trip types, intensity of use, total number of vehicles required to meet demand,

* Waymo plans to deploy 20,000 autonomous Jaguars in 2019 and 2020. If the company decides to deploy these, for example, in 20 different metro areas, a significant number of locations will have a very small number of autonomous vehicles on their streets.

† A case can be made, however, that past “network-scale” changes provide guidance regarding the possible impact that autonomous vehicles will have on the economy and society. This argument is discussed in Richard Mudge, “The Economic and Social Value of Autonomous Vehicles: Implications from Past Network-Scale Investments,” submitted for publication.

and relative share of occupied/unoccupied vehicle miles traveled); infrastructure insurance (transit, highways); and even residential insurance.

Outlook for Factors That Influence Technology Adoption

For the vehicle manufacturing and supporting industries, the primary factors that can affect the development and deployment of advanced vehicle technologies include the following:

- Change in the underlying business model, with a focus on travel rather than vehicles sold
 - Shift away from individually owned vehicles
 - Emergence of shared-use vehicles
- Regulations (federal and state)
- Software development and cybersecurity
- Consumer acceptance
- Market for data and concerns about privacy
- Available technology for vehicle-to-vehicle communication (a controversial subject—see section “DSRC versus 5G”)
- Institutional, including the insurance industry.*

For the insurance industry, the broad implications are straightforward: improving safety has the potential to reduce the volume of traditional automotive insurance, while also creating potentially new areas of opportunity. Yet those broad implications are just that—vague and inadequately defined to support actions.

Not surprisingly given the status of the industry, estimates of both the overall magnitude of the potential insurance market impacts and the timing vary widely. A recent study by KPMG, for example, estimated that by the year 2050 autonomous vehicle technology could shrink the auto insurance sector by 71% or \$137 billion, with declines beginning in 2018.⁸ Significantly, that estimate was revised since its initial publication just two years ago due to rapid change in the automotive industry.[†] A more dramatic forecast by ARK Investment Management predicts that if autonomous vehicles “go mainstream,” automobile insurance could be cut in half by 2030.⁹

On the other hand, a 2017 study by the Stevens Institute on behalf of Accenture projects smaller declines in traditional automotive insurance premiums and that those declines will be partially offset by new product lines—primarily cyber insurance premiums. In this instance, the overall decline in insurance premiums, factoring in this broader market, is projected to be 12.5% or \$25 billion.¹⁰

* This topic is explored later in this report—see section “Institutional Change.”

[†] In 2015, KPMG predicted that the transition from traditional vehicles to self-driving vehicles would be incremental, becoming the “new normal” by 2040. In 2017, leapfrogging technological developments revised that time frame to 2035—five years earlier than initially projected.

The first challenge in projecting possible outcomes is understanding technological changes in the vehicle industry, including those that are most likely to affect commercial and institutional relationships relevant to insurers, as well as the possible directions of institutional change.

DSRC versus 5G

There is an active debate underway in the United States concerning the best strategy for communication among vehicles and with roadside data systems, including both the need for dedicated spectrum and the specific technological solution requirements. For the solution design, a long-standing technological standard advocated by the U.S. Department of Transportation is dedicated short-range communications (DSRC), for which the Federal Communications Commission set aside wireless spectrum in 1999. (That was followed in 2008 by a similar action by the European Telecommunications Standards Institute.)

The DSRC technology solution has been tested and works, but the technology requires equipping vehicles with a DSRC radio as well as DSRC units along certain roadways. Toyota and GM plan to install these radios in some models over the next two to three years. 5G wireless is viewed as an attractive alternative long-range solution, in part since the costs to deploy it will be covered by cellular firms. This would still require that roadside equipment be outfitted to support wireless service, but 5G has not yet been designated as a standard that would make it possible to avoid the costs of the long-standing DSRC solution.

Spectrum remains another challenge. Due to intense competition for spectrum, some have argued for releasing the dedicated spectrum and instead relying on commercial solutions and spectrum, such as 5G cellular communication. Advocates of dedicated spectrum and technology, however, point to certain aspects of the strategy that require highly reliable communications to support safety applications. This debate is expected to continue for some time.

3. A Market-Based Automated Systems Framework

Vehicle systems engineers at the Society of Automotive Engineers (SAE) and the National Highway Traffic Safety Administration (NHTSA—part of the U.S. Department of Transportation) developed frameworks to classify and define the gradations of vehicle technology. These systems were merged into a single SAE system in 2016 and map out a detailed view of vehicle technology. The emphasis is on the nature of automated assistance and how that assistance is provided—mainly by either lateral or longitudinal control in response to the identification of an object or event.

The SAE work focuses on individual technologies and the progression along a continuum of vehicle automation system design. It does not, however, define technology from the standpoint of change in safety, driver responsibility and ownership. Yet it is these dimensions that ultimately define the implications for the market—and the insurance industry, in particular.

This report sets out a broader classification to frame technological advancements, one that combines common sense with a focus on market forces to discern the implications for the insurance industry. This framework includes three classes, summarized in Table 2 (the Appendix shows how these classes compare with the classes developed by the SAE and NHTSA).

Table 2
MARKET-BASED VEHICLE AUTOMATION CLASSES

System Class	Definition	Market Status
Safe	The driver is solely responsible, but technology can improve safety by giving alerts to risks or automating/improving the effectiveness of select driver actions, such as through automatic braking, electronic stability control, or blind-spot warning.	These technologies largely exist today and are offered in an increasing number of new vehicles today. Many have been proven to improve safety and/or reduce damage in the event of a collision.
Self	The vehicle can assume responsibility for select driving tasks under specific road or weather conditions, but an alert driver who is ready to take control is still required.	These emerging technologies will increase penetration over the next decade. Because their performance is subject to driver intervention, their safety benefits are not yet well documented.
Driverless	The vehicle is responsible for all driving tasks for the entirety of a journey. No driver is required at any phase. Current deployments may have geographic or weather limitations.	This technology has been implemented in low-speed applications. Waymo's deployment in Phoenix was the first widely available, public commercial application. Systems that can operate without a driver are still in development, and those that can travel "on all roads, all the time" could be more than a decade away.

The Safe, Self and Driverless perspective helps provide insights regarding implications for market development, insurance and public policy. Of these three categories, Safe and Driverless will have the greatest impact on vehicle safety and thus are particularly important to the insurance industry. Safe is most relevant for near-term vehicle fleets, whereas Driverless represents the ultimate impact.

A key distinction among classes in this framework is that neither Safe nor Self technologies will change the basic relationship between the manufacturer, the owner and the insurance industry. Driverless, however, will encourage fleet ownership and increased ridesharing; thus it is a significant departure point for the industry.

Further, while safety is expected to improve dramatically as human error is removed from driving, the generally accepted premise is that this will not happen until Driverless arrives and is commonly in use. This is clearly incorrect. Safety technology has already made an impact on passenger safety and is expected to continue to improve safety while also reducing the risk and of injuries, fatalities and property damage.

Each of these classes is discussed in greater detail here.

Safe Systems

Safe technologies improve the safe operation of a driver-operated vehicle by providing a warning or activating a safety system without requiring the driver to react or respond. Examples include:

- Electronic stability control
- Blind-spot detection
- Forward collision warning
- Lane departure warning
- Automated emergency braking (AEB) systems for both low-speed (beginning to exist) and high-speed (needing substantial improvement) situations
- Rearview (and later 360-degree) video systems
- Rear cross-traffic alert
- Low-speed collision avoidance systems (front, rear and pedestrian) coupled with automated emergency braking

Safe technologies are largely in place in the marketplace today, including those from the safety eras Safety/Convenience, Advanced Safety, and Advanced Driver Assistance (see Table 4).

Advances in safety depend on the quality and functionality of Safe technologies. Because many technologies in this group have been in the marketplace for a long time, the perception is that they are mature technologies. Many are, but most can and will continue to improve, just as seat belts improved from lap belts to lap/shoulder belts to lap/shoulder belts with crash pretensioners.

Public policy with an interest toward safety should focus on supporting the maturation of these technologies with the goal of automating actions such that the system controls the vehicle when necessary, and once the need has passed, it smoothly returns control of the vehicle to the driver. Antilock brakes and electronic stability control are examples of exactly this kind of mature technology.

Self-Driving Systems

This class includes the many assisted driving technologies that also require the driver to be ready to resume control of the vehicle. As with Safe systems, many are on the road or almost ready to go on the road, corresponding to what NHTSA has termed the Partially Automated Safety era:

- Collision mitigation systems

- Automated (also intelligent) cruise control
- Lane keeping assist (or automated lane keeping)
- Parking assist
- Part-time self-driving (in defined locations and weather conditions)

The last category applies to systems that can drive the vehicle but require that the driver be available to assume control in certain circumstances, such as when the vehicle reaches the exit on an expressway, encounters weather or road conditions it cannot handle, or travels into an area without adequate map accuracy.

Self-Driving systems represent a technology layer that is built on top of mature, high-quality Safe systems. That technology is focused on

- Delivering comfort and convenience to the driver without degrading safety, and
- Supporting routine driving* rather than emergency situations.

Its primary purpose is adhering to many, but not necessarily all, of the countless traffic regulations in different jurisdictions so the driver doesn't need to. These systems still need the driver to be able to drive the vehicle in situations that are challenging for the automated system. Safety is at best constant.

Self-Driving systems have important limitations. First, they require an alert driver who can take over control of the vehicle on certain roads, under certain conditions or in emergencies. Second, these systems do not operate in all environments. They have geographic or other limitations, such as speed ranges or weather conditions (for example, rain, fog or snow). In all cases, the driver must be aware of these requirements and limitations. For these reasons, Self-Driving systems present more complex challenges in designing for human behavior than either Safe or Driverless.

The near-term focus of many OEMs today is on this technology class. GM's Cadillac Super Cruise is a good example: a high-end vehicle system that will drive itself on certain roads under certain weather conditions and will remain engaged so long as the driver remains alert and ready to assume control.

Since these cars need a driver, ownership remains the same; however, because comfort and convenience may be enhanced significantly, both trip demand rate and trip length could increase once these systems are mature.

* Examples include low-speed stop-and-go travel during congestion or travel on limited access roadways.

While a growing number of new vehicles have some (and in some cases, all) of these technologies, the vehicle fleet still falls well short of full deployment. Therefore we are still at an early stage in our ability to improve safety and reduce injuries, fatalities and property damage.

Driverless Systems

Driverless systems are those that enable vehicles to operate with no human involvement. This includes applications that may be limited to certain roads throughout a geofenced area and in some weather conditions—without imposing any new restrictions on conventionally driven vehicles in those areas in those weather conditions. The key to the evolution of this technology is making large geofenced areas and reducing restrictions on weather conditions for these vehicles to be able to travel on “all roads, all the time.”

Driverless systems reflect the highest quality of Safe and Self system features that adhere to all the traffic regulations within the system’s operating/driving domain. These systems operate without a driver as well as or better than with an attentive human driver.

Driverless vehicles will have the broadest impact on transportation and society in general by

- Increasing safety to the highest level feasible through technology alone;
- Reducing the cost of shared mobility relative to traditional vehicle ownership;
- Reducing traffic congestion—a controversial topic;*
- Improving accessibility for individuals with mobility impairments (such as the elderly, wheelchair users, visually impaired users and others with limited or reduced ability to drive); and
- Improving access, whether by increased roadway capacity or by longer trips due to the ability to multitask (such as making calls, answering emails, watching videos, or even sleeping).[†]

* Driverless technology is generally expected to improve road capacity due to reduced intervehicle spacing, increased ridesharing and fewer crashes, although there is a great deal of uncertainty about the magnitude of the improvement. A few studies even predict the opposite: reduced capacity due to increased vehicle-miles traveled associated with empty backhaul and AV repositioning in off-peak and possible increased traffic due to the “induced demand” effect.

[†] This implies a reduced value of travel time, with important implications for existing travel demand models and the possible encouragement of longer trips and more dispersed urban regions.

Early forms of driverless vehicles exist today and have been deployed in select markets, such as low-speed travel on campuses and local streets.* In addition, Waymo introduced driverless taxis to a group of several hundred volunteers in late spring 2018 in a suburb of Phoenix, Arizona. The company has ordered 62,000 Chrysler Pacifica vans and 20,000 Jaguar SUVs to support future deployment of autonomous shared vehicles, with deployment planned for 2019, 2020 and 2021. Waymo is “interviewing” urban areas for possible deployment, with a preference for large cities with good weather (no snow) and favorable local regulations. Uber has ordered 2,400 vehicles from Volvo and, prior to the recent fatal accident in Tempe, Arizona, expected to deploy autonomous shared vehicles in 2019, 2020, and 2021.

OEMs are also developing driverless technology. GM, for example, purchased Cruise, a company that was developing a driverless vehicle. It recently announced that this technology could be integrated into its production line for the Chevy Bolt and has mentioned 2019 as a possible time to begin deployment. During mid-2018, Cruise received additional investments from Softbank (\$2.25 billion), GM itself (\$1.25 billion), and Honda Motors (\$2.75 billion).

Clearly solutions are advancing rapidly. Nonetheless, driverless vehicles are expected to begin to appear in meaningful numbers within the next 3 years and could achieve broader market penetration within 10 years. Instead of an individual driver, these vehicles will be managed by a central controller as fleets of interchangeable vehicles that can be dispatched to serve individuals and groups of riders originating at about the same place at the same time going in the same general direction. This shared-ride functionality will lead to improved utilization and efficiencies.

Importantly, these facts mean that the ownership model will be different from that which exists today. Use will be by many individuals rather than by a single owner. Instead of individual owners as the dominant model, a fleet owner will be more practical. Demand will be affected by pricing and service, which may well be best in moderately dense, so-called transit-oriented land uses. Person miles traveled are likely to increase, while vehicle miles traveled are likely to decrease proportional to the growth in ridesharing.

For this technology, public policy focused on making ridesharing attractive will be critically important.

* Examples include personal automated vehicles deployed in Babcock Ranch, Florida; Bishop Ranch, California; and Greenville, South Carolina, in 2018. Babcock is a planned 50,000-person community near Fort Myers, Florida. Bishop Ranch is a new development. Greenville deployed low-speed driverless vehicles at a large office park, followed by deployments to two residential areas.

4. History and Outlook for Advanced/Automated Vehicle Systems

Information technology has shaped many of the most important advances in vehicle safety systems over the last 50 years, starting with early Safe systems such as antilock brakes and electronic stability control. The pace of change has increased over the last three decades, however, coincident with the advancement and maturation of advanced technologies. In practice, almost all vehicle safety systems continue to evolve long after their initial introduction, though the incremental impact of those changes on performance diminishes over time.

Today, while many of the core technologies to support advanced vehicle automation have already been introduced in one form or another, many are still in an early stage of the development and maturation cycle. Yet the complexity of solutions is also increasing as developers and manufacturers capitalize on individual safety system elements, such as radar or video, and integrate them with other systems to field more advanced systems requirements, such as AEB or the even larger suite of automation Tesla calls AutoPilot.

Only just beginning to appear, and yet to be introduced as a commercial product, is the far more complex Driverless system. Driverless solutions are by nature a broad integration of many of the subsystems that have only recently entered the market, coupled with advanced systems and software logic.

These extremely complex systems are expected to continue to advance rapidly over the next 5 to 10 years, though the rate of advancement and the market penetration will depend on improvements in the underlying technology and software development, notably supported by artificial intelligence (AI).

This section summarizes one of the challenges for developers and regulators—standardization—as well as three recent efforts to document the evolution of vehicle safety systems and technology and its possible impacts (from NHTSA, the Aspen Institute and the Regional Plan Association). Together, these begin to shape a clearer understanding of the direction and possible impacts of the industry, including the outlook for Driverless systems.

Striving for Standardization

One of the most basic, important and surprisingly challenging aspects of vehicle automation is standardization. One aspect has already been discussed; namely, the framework for classifying and managing vehicle automation. The industry has generally settled on SAE's levels to organize and manage systems, and this report advances a second standard (Safe, Self and Driverless) for considering the market, operational and business dimensions of these technologies.

Yet two vital aspects of standardization have yet to be addressed: nomenclature, the need for a consistent name for each technology, and functionality, or how well the technology works. Answers to both of these topics are needed to ensure that the automotive industry and its customers deploy these technologies in the most effective and safest way possible.

Nomenclature

It should not be surprising that in a competitive environment, each developer and manufacturer is introducing and naming its own technologies independently. This has led to confusion over the intention and functionality of vehicle technologies. Table 3 presents an example of the many names currently being communicated for automated emergency braking.

Table 3
 SAMPLE CHALLENGES WITH TECHNOLOGY NAMING:
 VARIATIONS IN MANUFACTURER NAMING OF AUTOMATED EMERGENCY BRAKING SYSTEMS

MAKE	NAME/PACKAGE
Acura	Collision mitigation braking system/AcuraWatch Plus
Alfa Romeo	Forward collision warning <i>or</i> Forward collision warning plus
Audi	Pre sense front <i>or</i> Pre sense city
BMW	Frontal collision warning with city collision mitigation <i>or</i> Collision warning with city braking function
Buick	Front automatic braking
Cadillac	Front and rear automatic braking <i>or</i> Low-speed forward automatic braking <i>or</i> Automatic collision preparation
Chevrolet	Front automatic braking <i>or</i> Low-speed forward automatic braking and front pedestrian braking <i>or</i> Low-speed front automatic braking
Chrysler/Fiat/Jeep	Full-speed forward collision warning with active braking <i>or</i> Full-speed forward collision warning plus
Ford/Lincoln	Pre-collision assist with pedestrian detection
Genesis	Automatic emergency braking
GMC	Low-speed forward automatic braking <i>or</i> Front automatic braking <i>or</i> Forward automatic braking
Honda	Collision mitigation braking system/Honda Sensing
Hyundai	Automatic emergency braking
Infiniti	Forward emergency braking <i>or</i> Intelligent brake assist <i>or</i> Forward emergency braking with pedestrian detection
Kia	Autonomous emergency braking
Lexus	Pre-collision system/Lexus Safety System+ <i>or</i> Pre-collision system with pedestrian detection/Lexus Safety System+ <i>or</i> Pre-collision system with advanced driver attention monitor/Lexus Safety System+
Mazda	Smart city brake support/smart brake support
Mercedes-Benz	Collision prevention assist plus <i>or</i> Active braking assist
Mini	Frontal collision warning with city collision mitigation
Mitsubishi	Forward collision mitigation system
Nissan	Forward emergency braking <i>or</i> Forward emergency braking with pedestrian detection
Porsche	Adaptive Cruise Control + PAS Porsche Active Safe
Subaru	Pre-collision braking/Eyesight
Toyota	Pre-collision system with pedestrian detection-TSS-P <i>or</i> Pre-collision system-TSS-C
Volkswagen	Front assist with autonomous emergency braking
Volvo	Collision warning with full auto brake and pedestrian detection <i>or</i> City Safety

Source: Consumer Reports, "Guide to Automatic Emergency Braking"; June 29, 2017.

Different naming conventions present more than a marketing challenge. They also complicate tracking deployment of these systems and lead to confusion among consumers about the functionality of the associated system.

Vehicle System Functionality

Given that multiple manufacturers are developing and fielding similar vehicle systems, and that those manufacturers decide independently which sensors to use to support those systems and the rules for when and how they work, the industry faces an important challenge: how to classify, judge and manage the relative performance of each system.

A study by AAA showed, for example, that AEB system performance varies widely. Just as important, drivers are simply not familiar with the fact that different manufacturer systems perform differently: “two-thirds of Americans familiar with the technology believe that automatic emergency braking systems are designed to avoid crashes without driver intervention. The reality is that today’s systems vary greatly in performance, and many are not designed to stop a moving car.”¹¹

As for video systems, NHTSA has been working with manufacturers to deploy systems voluntarily rather than by requiring it through regulation. This tactic has proven successful in accelerating deployment, with 20 auto manufacturers, representing 99% of vehicle sales, having committed to making AEB systems a standard offering on all new vehicles by 2022.¹²

While this represents important progress in deploying technology, consumers remain largely unaware of system performance variations and limitations. They also often do not make use of existing technology, either consciously or by accident. In sum, the insurance industry faces a series of challenges in understanding the effective performance of these new technologies.

NHTSA’s Five Eras of Safety

The National Highway Traffic Safety Administration has identified five eras of vehicle safety. Table 4 summarizes NHTSA’s views on technologies and time frames, slightly adjusted to reflect some recent developments.

Table 4
 NHSTA’S FIVE ERAS OF SAFETY (time frame of initial commercial introduction)

Years	Era	Features
1950–1995	Safety/Convenience	Seat belts* Cruise control Antilock brakes* Improved lighting (including high-mount brake lights)* Airbags*
1995–2010	Advanced Safety	Electronic stability/traction control* Blind-spot detection Driver alertness detection system Forward collision warning Lane departure warning
2010–2016	Advanced Driver Assistance	Automated cruise control Rearview video systems* Parking assist Collision avoidance (forward, rear and pedestrian) coupled with automatic emergency braking Rear cross-traffic alert
2016–2025	Partially Automated Safety	360-degree video and sensing systems Lane-keeping assist Adaptive cruise control Traffic jam assist Self-parking
2025+	Fully Automated Safety	Driverless

*Requirements or specifications set by regulation or law

Source: National Highway Traffic Safety Administration’s “5 Eras of Safety” with select updates. Solutions from all eras prior to 2016’s “Partially Automated Safety” report are mature, proven systems that are generally available in the market—and in certain cases, required due to regulation. While some of the systems, such as lane keeping assist and adaptive cruise control, in the period 2016 and forward have been made commercially available, these systems are only now achieving broader market penetration. The fact that they have been introduced in a given time frame does not mean they are final. Most systems continue to evolve and improve as technology improves.

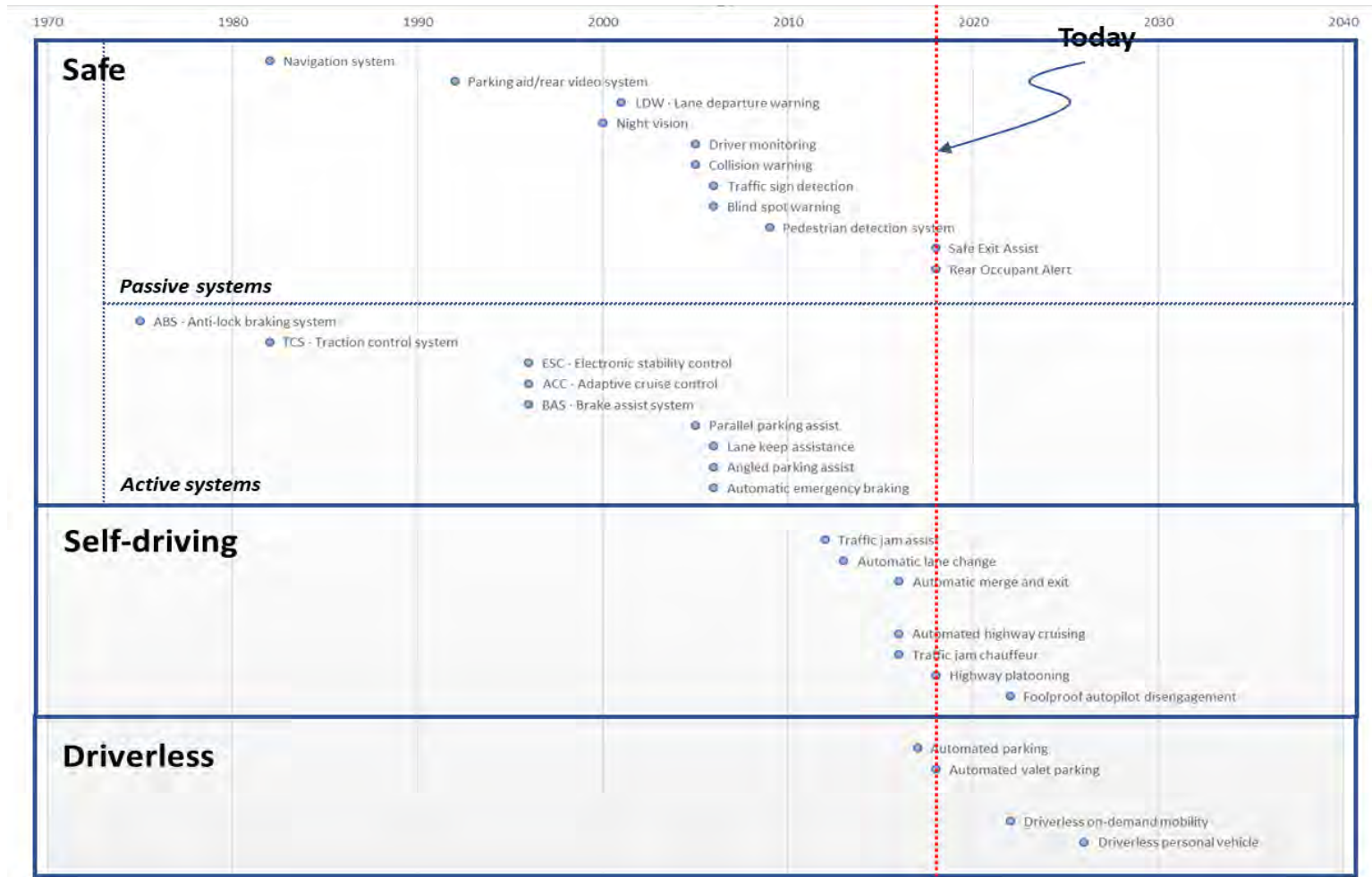
Vehicle Technology Introduction Mapped to Automation Classes

In 2017, the Aspen Institute summarized the evolution of key technologically based safety systems, starting with their initial appearance in the marketplace.¹³ That report’s estimates are presented in Figure 1, which includes an overlay of this report’s market-based technology classes to place the nature of the evolution into context for this study. The figure shows the date when each technology was first introduced. The date for common introduction into production vehicles is usually several years later.

Even so, the chart does show that most of the key Safe technologies have been developed and are being deployed.

In short, the Aspen study's projections emphasize what NHTSA's five eras demonstrate: many technologies have entered the marketplace, and while the level of maturation and market penetration varies widely and technologies may still be introduced (such as Safe Exit Assist in 2018), we are now at the start of the final phase of technology introduction—Driverless.

Figure 1
 VEHICLE AUTOMATION TECHNOLOGY INTRODUCTION TIMELINE



Source: Primary data from Bloomberg Philanthropies/The Aspen Institute (2017).

Technical Note: Automated Vehicle Sensor Systems

Automated and autonomous vehicles today rely on a combination of one or more of four sensor types: sonar, cameras, radar and lidar. Each has its own strengths and weaknesses. Commercial systems, such as Tesla's, today rely on a combination of sonar, cameras and radar, avoiding the more costly lidar. Nonetheless, the industry generally agrees that adding lidar will enable more advanced automation. Each technology has advantages and disadvantages.

- **Sonar** is a proven, inexpensive technology used by the vehicle industry for short-range object sensing, useful for applications such as automated parking or blind-spot detection. Sonar does not, however, have the range to support broader automation applications.
- **Cameras** can capture high-resolution color images but cannot measure either the velocity of remote objects or distances with any precision, and performance may degrade in certain lighting conditions.
- **Radar** can measure both distance and velocity, and automotive radars are more affordable than lidar. Radar works best at shorter distances and performs well in varying weather conditions, but because it uses radio waves, it is not good at detecting and/or mapping fine details at large distances.
- **Lidar** can measure distances with high accuracy (like radar), can measure velocity, and is less subject to interference from differing lighting conditions. Importantly, it also offers higher resolution than radar, which makes lidar better at detecting smaller objects and allows the system to classify them more accurately as pedestrians, vehicles, or other objects. Developers are working to build in the range that manufacturers ideally want for a lidar system to support automation of 200 to 300 meters. Lidar is the most expensive sensor for vehicle automation in the market today. It is also subject to performance loss in certain weather conditions, such as snow.

Lidar systems are either mechanical or solid-state. Frost and Sullivan estimate that 90% of all driverless cars in development rely on solid-state lidar systems, making it the most popular, generally due to (1) safety and critical reliability of solid-state, (2) lower expected per-unit costs, and (3) performance.

Phases of Automated/Autonomous Vehicle Introduction and Impacts

Given that the Driverless era is upon us, the next logical question is, when will the systems and solutions supporting Driverless be commercially available—and achieve a meaningful market penetration?

The answer depends in part on which aspect of Driverless capabilities are of interest. Early-stage solutions have clearly entered the market:

- Low-speed autonomous shuttles and related forms of “micro transit” are commercially available today and are beginning to appear in more cities in local service roles on fixed routes.

- Heavy-duty commercial truck applications have also begun to appear in limited trials and under select operating environments. For now, these have been limited to highway driving, leaving the more complex “last-mile” requirements for the next generation of vehicles.
- Autonomous taxis have also appeared, but today they are geofenced to limited roads and only operating in true Driverless mode in Arizona, where weather will not adversely affect operations.

Yet these represent only a small part of today’s total potential marketplace.

Beyond examining the outlook for individual technologies or systems, it is important to step back and consider the broader evolutionary implementation and impact of automated vehicles. The Regional Plan Association (RPA) for the New York–New Jersey–Connecticut metropolitan area recently issued a projection for the implementation of these technologies.¹⁴ The key conclusions as they relate to AV market penetration, timing and impacts are summarized in Table 5.

Table 5
PHASES IN AUTONOMOUS VEHICLE DEVELOPMENT AND IMPACTS

Phase	Period	Impacts
1. Automation technology improves, costs decline	2017–2022	<ul style="list-style-type: none"> • Microtransit services provide a flexible, high-occupancy solution. • The use of on-demand service increases. • Automakers partner with transportation network companies to test Level 3 on-demand services with drivers still behind the wheel
2. AVs enter the market	2022–2027	<ul style="list-style-type: none"> • Some micro transit services will become autonomous; cost of a shared ride will drop to one-third that of a private, on-demand vehicle. • Autonomous platoons of freight vehicles will revolutionize goods movement, mostly on highways. • Vehicles licensed by MYC Taxi & Limousine Commission will incorporate Level 4 technology.
3. AV truck markets mature	2027–2040	<ul style="list-style-type: none"> • AVs will be routed flexibly and dynamically, increasing roadway capacity. • Smart devices carried by pedestrians may be able to communicate with AVs for an extra level of safety. • Charging stations for electronic vehicles and other wayside infrastructure will incorporate vehicle-to-infrastructure (V2I) communications. • Street parking will be converted to open space or bike lanes.
4. Urban and suburban land use changes	2040+	<ul style="list-style-type: none"> • Traffic lights will be removed. • Transit agencies will use autonomous technology to adapt flexibly to demand and provide services in low-density areas and at off-peak hours. • Drivers will reclaim commuting time for leisure and work-related activities. • Vehicle crashes will fall by 90%. • Parking need will be cut by up to 1.4 million acres nationwide, allowing parking lots to be converted to open space and affordable housing developments.

Source: *New Mobility: Autonomous Vehicles and the Region*, Regional Plan Association, October 2017.

Outlook for Safety Improvements

Documentation of the safety benefits of automated Safe systems is only just beginning, and considerable variation in performance exists among OEM systems. In fact, recent research has shown that vehicle owners are disengaging safety systems due to either suboptimal performance, not clearly understanding their benefits, or both.¹⁵

Consequently, the relative safety benefit of a given manufacturer's system when including exposure to injuries, fatalities and property may either not be well documented or not yet be publicly available. This leads to some important conclusions regarding advanced systems safety:

- System performance varies widely.
- Systems testing and reporting is critically important to ensuring that the most effective technologies advance.
- Benefits of advanced systems will affect certain aspects of safety, but insufficient research exists at this point to draw conclusions regarding the broader impacts on collisions, injuries and fatalities.

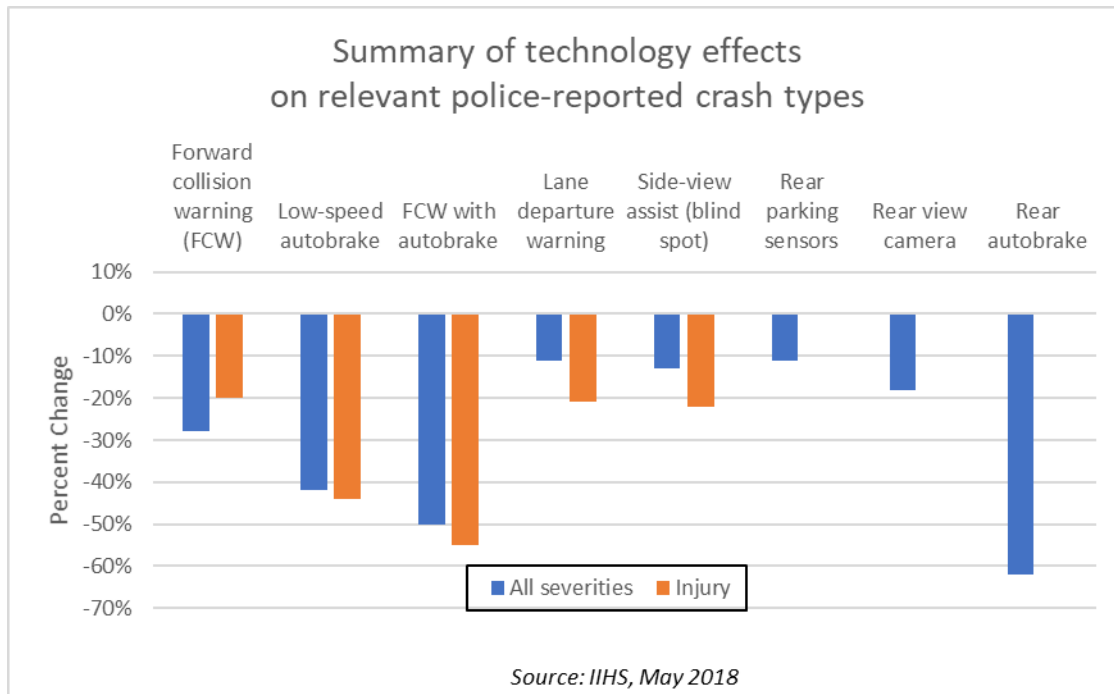
This section summarizes one recent series of studies on vehicle safety systems and then summarizes the broader market outlook.

Initial Safety Performance Results

The IIHS has begun testing various automated safety systems and has found that certain systems can deliver significant improvements in vehicle safety. Figure 2, for example, shows the results of IIHS research on various systems and the associated percentage change in injuries reported for vehicles equipped with a given technology. Note that these results vary widely by circumstance and manufacturer, but initial findings are encouraging.

Autobrake, for example, which is referred to in this report as AEB, has been shown to significantly reduce forward collision injuries, particularly when coupled with forward collision warning (FCW)—IIHS estimates by 50% or more. Lane departure warning also shows important benefits, though IIHS reports that small samples and high variability raise uncertainty regarding this early testing, averaged result.

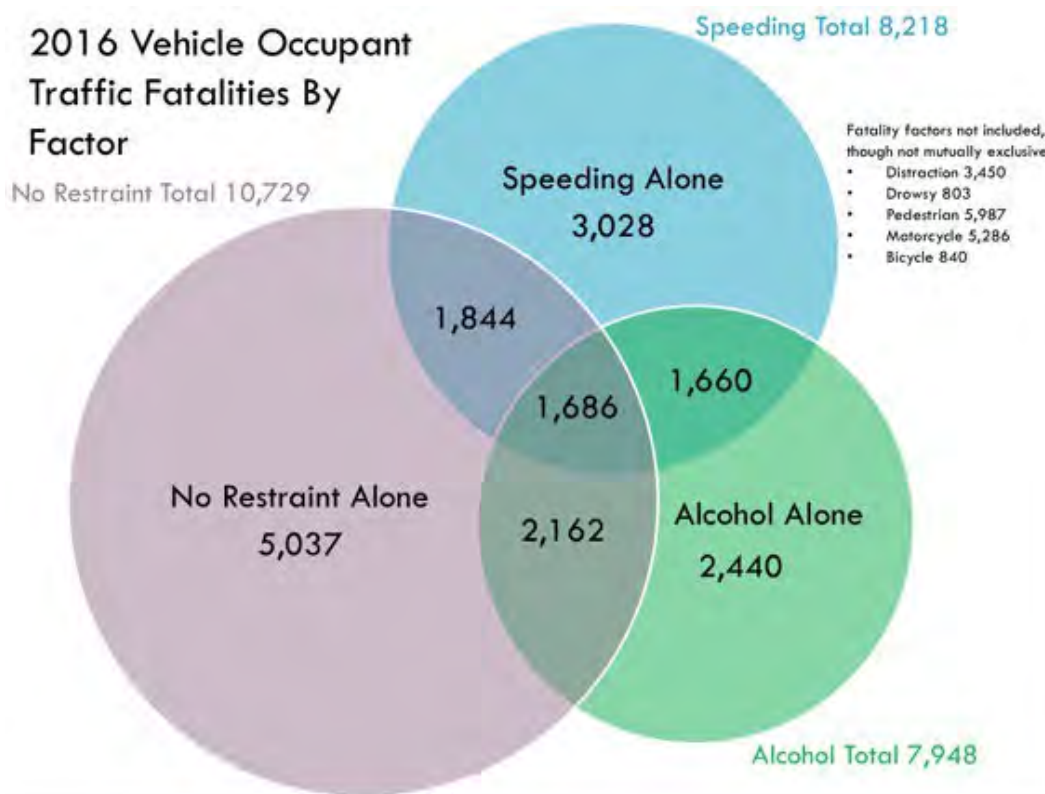
FIGURE 2
SUMMARY OF TECHNOLOGY EFFECTS ON RELEVANT POLICE-REPORTED CRASH TYPES



Safety from Safe Systems to Driverless

Safety systems will clearly improve safety and reduce injuries and fatalities on a broad scale in specific circumstances. An examination of the nature of accidents, however, suggests that these benefits will not directly correlate to broader safety metrics since the specific factors leading to a crash may or may not be addressed by a given safety system. Figure 3 shows how a recent analysis by ARK Investment Management found that fatalities due to speeding, alcohol and no restraints (seat belts)—either alone or in some combination—comprise a large share of total traffic fatalities. While Safe systems (AEB, for example) may reduce the severity of many crashes, they are not likely to prevent the crashes themselves.

FIGURE 3
2016 VEHICLE OCCUPANT TRAFFIC FATALITIES BY FACTOR



Source: ARK Investment Management LLC analysis of NHTSA data, 2018.

Considering this, it is apparent that while Safe systems will continue to improve safety incrementally, only Driverless systems—in which the system controls vehicle operation completely—will be able to realize the largest gains in safety. Those gains will, of course, be specific to those vehicles, so the share of driverless vehicles on the road will decide the rate of improvement.

5. Institutional Issues

The debate over autonomous vehicles usually focuses on the technology itself, with an emphasis on when such vehicles might become available. These conversations are interesting and important. At the same time, however, profound changes have already taken place regarding the institutions that shape transportation, with more change coming. These changes should be examined in parallel with technology.

Important events in the economic history of transportation in the United States concerns economic deregulation of airlines, intercity trucks and the railroads. These changes occurred in the late 1970s and early 1980s and transformed much of surface transportation, generated new services, reduced prices and costs), and stimulated significant growth in demand and economic activity. Urban transportation remained regulated, with limits on the ability of private firms to compete with public transit or local taxis.

Over the last five years or so, this has changed dramatically with the advent of so-called transportation network companies (TNC). Uber and Lyft are the best-known TNCs, but they face a growing number of competitors (some backed by automobile OEMs). The TNC business model is based on shared assets. The average automobile is used less than 5% of the time. In North America TNC firms have largely been successful in providing higher quality service for passenger transportation at prices that are usually lower than taxis but higher than transit. Despite the attention given to the rapid growth of TNCs, they still account for a small share of overall travel—Uber handles about 5 million trips a year versus the 1 billion total trips in the United States.

Some analysts are calling for new fees to reduce the advantage of TNCs (perhaps with receipts used to aid mass transit).¹⁶ Some cities (Chicago, for example) have responded by adding new fees or regulations regarding driver safety. Some countries in Europe (Germany, France and others), on the other hand, have outlawed these services. New York City recently imposed a cap on the number of TNC drivers (similar to the existing cap on the number of taxi medallions) and added a fee for TNC use.

Uber and Lyft (and most of their competitors) view autonomous vehicles as key to their ability to finally become profitable. Without the need for a paid driver and with even more miles driven per vehicle, operating costs per mile will drop dramatically (costs per passenger mile drop even further for shared travel). Some firms talk in terms of 20 cents a passenger mile¹⁷ or even less. This would at last allow these firms to become profitable and would likely generate profound changes in the volume of vehicle travel (most likely a significant increase due to lower costs) and in the types of trips taken.

Part of the motivation behind these changes comes from a new view of transportation. Adam Jonas from Morgan Stanley has provided a succinct summary, contrasting the Silicon Valley view of vehicle transportation with that of traditional auto manufacturers.¹⁸ The new focus is on the time spent in travel rather than on the number of vehicles sold. Shared mobility is a key part of this concept since it reduces the cost of travel and diverts people from owning individual vehicles.

One significant result has been a shift in leadership within surface transportation. For more than 100 years, the public sector has dominated roads and transit development. It builds the infrastructure (and raises the funds to do so in the process) and determines where and when to add capacity. The private sector responds by selling vehicles to individuals or to public transit monopolies. This model is about to be turned on its head. Autonomous vehicles will shape how transportation is provided. A key part of their business model is to react to the characteristics of existing transport infrastructure rather than waiting for the public sector to change to make their technology easier. Transportation agencies are increasingly interested in actions that might help autonomous vehicles (better lane markings, for example).

In the future, however, the public sector will respond to the needs of these new vehicles and the organizations that own them. This implies greater emphasis on lane markings and signs and a reduced need to add new road capacity or new fixed rail transit. Many believe that public transit as we know it today will not survive—group travel will still happen and likely increase, but it will probably be managed by private entities (either on their own or in partnership with public agencies).

To date, public agencies have not been able to incorporate the changes in technology and shared mobility into their planning models. New techniques are needed (*scenarios* has become the word of the day). One problem is that many public agency staff remain skeptical concerning the pace at which autonomous vehicles will be deployed. This skepticism draws on concerns over the speed of technology development, the need for federal regulations to mandate vehicle connectivity and concerns over the pace of fleet turnover.

One sign of this change has been the leadership by the private sector in research and development. Over the past five years private firms have spent some \$80 billion in developing the technologies needed to make automated and autonomous vehicles practical.¹⁹ Although the firms behind this massive level of spending include traditional transport firms (most of the large OEMs), much of the leadership has come from firms with no history of involvement in vehicle manufacture or transport operations. Google (and its new subsidiary, Waymo) and Tesla have received much of this attention, but the number of new players is impressive. The California Department of Motor Vehicles reports that more than 50 individual firms have signed up for the right to test autonomous vehicles in the state.

One clear implication is the importance of regulations. There is active debate regarding how best to move forward and ensure safety without limiting research and development, and there are many open questions:

- What are the appropriate roles for federal regulators (NHTSA, in particular); the individual state departments of motor vehicles; and some local governments, such as San Francisco, that want to be involved?
- When will these agencies mandate specific technologies, if ever (see, for example, the list of technologies shown in the tables earlier in this report that summarize Safe and Self-Driving vehicles)?

- Will these regulations slow the pace of deployment or serve to provide more precise definitions of vehicle characteristics?
- While a narrower definition of an autonomous vehicle might limit new concepts, will it also reduce uncertainty for the insurance industry?
- Will these regulations have implications for liability and insurance (perhaps even including mandates)?²⁰
- How will new regulations handle cybersecurity (some view this as the major risk for the development of autonomous vehicles)?
- How will regulations influence who owns the data generated by these vehicles (a major potential source of revenue and possible risk regarding privacy)?

In sum, part of the development of autonomous vehicles involves the generation of many new institutions—and the weakening of some traditional groups. Regulations are increasingly important for the pace of deployment, the degree to which new technology may affect the insurance industry, and ultimately determining if mandates become an important part of defining the market or if regulators continue to encourage innovation and experimentation.

6. Trigger Points

Key questions facing the industry today are how fast technology will be adopted and, in turn, how long it will take to see market, behavioral, safety and societal changes. This section identifies a series of trigger points, factors that could hinder or accelerate the market and shape the nature of how technology is deployed. Tracking these elements can provide guidance regarding the pace of deployment for each of the three parts of the general framework already described: Safe, Self and Driverless. These can be organized into three groups:

- Institutional/regulatory
- Technology
- Market penetration rates

The key parameters and effects of these triggers is summarized in Table 6 and reviewed in more detail here.

Institutional/Regulatory

Institutional triggers revolve around actions by the state and federal governments that could slow or accelerate adoption and use. Specific possibilities include:

- **Regulatory requirements for a given technology.** Manufacturers currently have latitude to determine what sensors to use and how to deploy them to yield intended automation results. This spurs innovation and improvement, but it also increases risk by allowing for variation in operating characteristics and performance. This can lead to confusion or misunderstanding about functionality among drivers.

While regulatory requirements deliver more uniform safety performance results, active promulgation of rules generally requires more time than voluntary standards and is unlikely for the foreseeable future. The most recent vehicle system regulation was published in 2014, requiring rearview video in all new light vehicles produced starting in May 2018. Nonetheless, regulatory actions could improve standardization and driver-system interaction.

Possible candidates for future regulations would logically include those systems with the greatest potential safety benefits, such as rear cross-traffic alert, lane departure warning, blind-spot warning, and collision avoidance coupled with automatic emergency braking. It would help to prepare a simple table to track these technologies and any regulatory actions. This could be linked with the market-based tracking effort described later.

- **Requirement for installed vehicle technology information in the vehicle identification number (VIN).** Requiring system information in the VIN would allow accurate tracking of vehicle safety performance and audits in light of installed systems, making regulatory or risk estimation efforts more effective. Given the large number of different technologies that may be installed on

vehicles and the different number of software updates, important changes appear to be called for in the VIN system. These include a larger number of VIN numbers and probably a centralized database that could track changes made by OEMs.

Table 6
TRIGGER POINTS: KEY FACTORS TO TRACK THE PACE OF ADOPTION OF AUTOMATED AND AUTONOMOUS VEHICLES

Trigger	Notes
POLICY	
Regulatory requirement for a given technology (or application) promulgated.	Regulatory actions for specific technologies are rare today. Any specific requirements will likely speed up deployment, but they may also (1) slow innovation and (2) encourage firms to slow deployment in order to wait for action by NHTSA. New regulatory actions appear unlikely in today's environment.
Clarification of state versus federal regulatory responsibilities	Worries exist that inconsistent regulations among states might add to vehicle costs. Federal legislation to clarify federal and state roles could provide a more consistent playing field. There is a risk, however, of too much detail too early. Thus, the nature of legislation is at least as important as the legislation itself.
Requirement for installed vehicle technology information in VIN	Requiring system information in the VIN would allow accurate tracking of vehicle safety performance in consideration of installed systems, making analytic, regulatory or risk estimation efforts more effective. This would be a positive action in terms of both encouraging deployment and supporting analysis of technology effectiveness.
TECHNOLOGY	
Automated emergency braking	AEB is one of the most important automation applications with value for safe, self, and driverless vehicles. The effectiveness of current industry applications varies widely, and system performance parameters are not widely understood. Increased standardization could improve safety and speed up driverless solutions.
Rapid fall in cost of lidar systems; e.g., below \$500 per unit	Lidar units—generally considered central to effective Self-Driving and Driverless systems—cost into the tens of thousands of dollars. With increased demand and competition, prices have dropped in recent years, and further reductions are expected within the next three years, accelerating the deployment of Self-Driving and Driverless vehicles, possibly also supporting vehicle retrofits.
Costs and effectiveness of other sensors	While currently considered less important than lidar, these should be tracked as well. Improvements to hardware and software could significantly improve their performance. As with AEB, no industry standards currently exist.
Growth in vehicle cyber insurance	Cyber insurance is expected to become increasingly important in the AV space as applications become more advanced. Growth in this segment will reflect the rate of adoption and maturation.
VEHICLES AND VEHICLE USE	
Privately owned light vehicles and commercial light vehicles (e.g., taxis and small delivery vehicles)	The percentage of personally owned vehicles with Safe and Self-Driving systems should be tracked, ideally by technology, to monitor share and rate of growth. Within this group of vehicle types, share could be tracked by new vehicles manufactured (easiest) or VMT (more difficult) and PMT (most difficult). Variation across type of region is important (central business district, suburban, rural and so on.)
Ridesharing—measured as an increase in average vehicle occupancy	The market share made up by ridesharing is a key indicator of a fundamental change in vehicle use and AV adoption. Widespread ride sharing—reflected in average vehicle occupancy—would favorably affect demands on infrastructure, safety, ownership and insurance.
Driverless light vehicles—growth in driverless vehicle share of VMT or PMT <i>in a given market</i> to greater than 1% or higher (This should be examined by type of market—central business district, metro area, rural and by region of country such as areas with poor weather versus good weather.)	Driverless will precipitate changes in ownership models, safety and costs. The single most important trigger point will be when driverless earns a meaningful share—measured either in terms of given market, region or country. Although the specific trigger point cannot be defined today without more proven market data, a reasonable measure of meaningful market penetration is greater than 1% of VMT or PMT. These data should be tracked by type of location and region of country.
Driverless commercial vehicles—growth in share of driverless truck VMT to greater than 1% or higher (Detail by region is important—western states may grow faster than more densely populated eastern states.)	Because of its economic value, commercial VMT should be measured—as for light vehicles, when penetration is greater than 1% of VMT—but in this case, in two ways: <ul style="list-style-type: none"> • Partial automation: Commercial trucking is already pursuing platooning or operating driverless in restricted domains, such as highway miles only. This should lead to reduced labor costs and increased safety for the automated portion of the journey, with the risks of the remainder of the journey a function of safe/self technologies. • Full automation: This will reflect true end-to-end driverless VMT.

- **Federal regulatory guidance.** Congress has been considering legislation that would define state versus federal regulatory responsibilities within the field of autonomous vehicles. The most recent draft would focus safety regulations at the national level, within NHTSA. This legislation has been delayed due to concerns generated by the recent fatal accident in Tempe, Arizona. Passage of this legislation would be an important benchmark.
- **Safety assessments.** The National Transportation Safety Board (NTSB) reviews transportation crashes and identifies likely causes. NHTSA can be involved in vehicle crashes as well. These assessments are viewed as authoritative regarding causes. Autonomous vehicles have already been involved in fatal accidents and rulings by NTSB to allocate responsibility among the automated vehicles, other vehicles and drivers will be important in helping to shape state and federal regulations and public opinion in general. Monitoring these rulings will shed light on the effectiveness of the underlying technology. This applies to all three of the categories—Safe, Self, and Driverless. The nature of the problems identified will help as well. For example, NTSB’s review of the Tesla fatality in Florida in 2017 highlighted the need to ensure driver attention for self-driving vehicles. A review of the Uber crash in Tempe, Arizona, showed that the sensors worked properly, but the emergency braking system had been disabled and the safety driver was not watching the road. Both of these examples indicate problems that could be fixed.

Technology

Although the initial generation of many underlying technologies and sensors has already been fielded, much work remains to refine the performance of those systems to reduce false warnings* and ensure that systems work when most needed.

Automated technology improvements will naturally lead to reduced risks for all vehicle types. Uncertainty currently exists regarding how a given manufacturer’s technology works under different circumstances and relative to others. This may become evident through testing, standards and/or simply historical performance.

Perhaps the two most important technologies to support accelerated market penetration are AEB and lidar systems:

- **Automated emergency braking standardized.** Increased standardization would enable more effective Self and Driverless automation. AEB is one of the most important automation safety applications, yet developers and manufacturers are deploying systems whose domain and performance both vary. These parameters are not broadly understood and increase risk.
- **Lidar costs fall.** Should the cost of lidar systems fall to a nominal cost—for example, below \$500 per unit—improved self-driving and autonomous deployments are expected to accelerate. Low-cost sensors in use today include sonar, radar and camera-based systems. Most developers

* This is a sensitive topic. Ignoring too many false warnings can also result in crashes, as apparently was the case with the fatal Uber crash in Tempe, Arizona.

deploy a combination of these for Self-Driving automation. The general consensus at this time, however, is that lidar is a requirement to advance vehicle automation into Driverless.

Currently, lidar units cost into the tens of thousands of dollars, depending on design and functionality. Reduced costs, which are expected to be realized within the next two to three years, should trigger much broader integration of this important technology into Self-Driving systems and accelerate the development and deployment of Driverless systems. The market for lidar devices has changed in recent years from a single supplier to dozens of new firms. At the same time, there is growing interest in other sensors. This means the high cost of lidar units may be less of a problem over the next few years.

Vehicles

Ultimately, the most important leading indicators of market transformation are in vehicle use. Unlike the conventional automotive market, however, the best measure of the transformation will not be vehicles sold. After all, shared use is the core value proposition of autonomous vehicles. Instead, measures need to be targeted to the intensity of vehicle use. For passenger vehicles, this would ideally be measured as passenger miles traveled (PMT)—either in total or as a share of all PMT—or secondarily, vehicle miles traveled (VMT)—again either in total or in share of VMT, tracking for when penetration is greater than 1% of VMT.

For commercial vehicles (perhaps divided between light- and heavy-duty commercial), activity would ideally be measured based on ton-miles and, because of the already emerging distinction emanating from platooning and highway-only driverless, between partial automation and driverless. Given the broad scope of the market and considerable uncertainty, the key metric will need to be ton-miles or VMT greater than 1%.

As described previously, the number of individual technologies that can help make vehicles safe is numbered in the dozens. Data on the market penetration for these technologies is difficult to find. Efforts to quantify the sale of vehicles with these technologies and their overall market penetration would be useful. These data could be compared with regulatory actions to mandate certain technologies—indeed, collecting these data might assist NHTSA in selecting the most effective regulations.

As more safety-related technologies are deployed, data regarding their actual impact on safety will increase. These data will provide real-world evidence regarding safety implications and need to be tracked and summarized. At present, no consistent source of such data exists.

7. Conclusions

The rapid pace of vehicle systems deployment, the broad array of both technologies and systems, the imprecise language used to describe those systems and their benefits, and the uncertain outlook all combine to create a confused sense of the current state of advanced and automated systems.

This research has sought to frame the various developments and industry research to identify the common themes, the status of the industry and the key factors that will drive the next wave of innovation and change.

On the basis of this review, several key conclusions can be drawn regarding the industry and outlook:

- **Autonomous vehicles are here.** There is a great deal of interest in when autonomous vehicles will appear, but it is now clear that they have arrived—albeit in narrowly defined applications, such as within office parks, on predefined routes, or in specific geographies. The question must now be rephrased to, when will more capable autonomous vehicles arrive? The general consensus for broader market penetration and impacts is by 2025—sooner than many originally thought. Also, there is no agreement regarding what it means for autonomous vehicles “to arrive.” What level of market penetration is enough? What fraction of the population needs to have access?
- **Safety gains will be made in advance of Driverless vehicles.** Many expect the maturation and large-scale deployment of Driverless technologies to lead to a sudden, rapid improvement in vehicle safety. This report concludes that instead the industry can expect safety to continue to improve incrementally through the maturation and adoption of Safe vehicle systems. These are already well on their way, with most new cars equipped with key technologies. Driverless technology will continue and advance the trend of improving safety rates, particularly in those areas affected most by driver behavior, such as speeding or drug/alcohol use, but incrementally rather than dramatically.
- **State and federal regulatory agencies will increase both support and restrictions.** As a better understanding of the role of the public sector becomes clear, state and federal regulatory agencies can provide improved support, such as infrastructure, while also engaging the industry in standardizing designs and reporting salient performance information.
- **System standardization and deployment will increase.** As vehicle automation/safety systems mature, and lacking any regulatory requirements, the industry will begin to converge on system standards and performance characteristics. This will help the insurance industry, but until then a lack of standards and information on market penetration by system will interfere with efficient documentation and actuarial estimations. The set of regulatory rules has yet to stabilize and will likely be influenced by public perception regarding the safety of Driverless and Self-Driving vehicles.

- **Vehicle communications to other vehicles and infrastructure (V2x) systems in support of improved, safer driving will cause a paradigm shift.** Systems will migrate away from a U.S. public-sector-defined requirement into a standardized, commercially available product that can accommodate all communications, including the broader cellular network. There is active debate on this topic, with some OEMs (GM, for example) still supporting the initial DSRC technology standards and others, such as Ford, planning to capitalize on broader solution suites that can integrate new technologies, including 5G wireless communications. The details of all this depend on the government retaining existing, dedicated spectrum to support transportation application.
- **Data ownership will grow in importance.** Since Self and Driverless systems are largely self-contained and do not report externally to the system manager and/or OEM, securing data to support system management and regulatory actions will grow increasingly important. At the same time, it will also be vital to the systems managers and OEMs as a source of competitive advantage and value capture, meaning that we should expect a difficult transition in the debate on data ownership, sharing and security.
- **Driverless will begin to appear in select domains, not broadly.** Driverless systems will appear first in narrowly defined domains, such as office parks; college campuses; individual communities, including those with predictable road and weather conditions such as in Phoenix; or select transit routes. Systems will likely then begin to appear in increasingly less-restricted domains, such as larger neighborhoods or regions within cities, but still with geographic and/or weather limitations.
- **Driverless leads to growth in fleet ownership.** The advent of Driverless systems represents an important departure point because it will make it possible to significantly increase commercial vehicle utilization over current personal vehicle rates without a concurrent increase in labor costs, meaning the ownership and operating cost per mile will fall. This will lead to more fleet-owned vehicles, where the commercial benefits will improve the competitive standing of owners of these systems.
- **Driverless vehicles will cost more.** This is certainly true today given the high cost of technology (lidar, in particular). This also increases the cost of vehicle repair, even as the number and severity of personnel injuries declines. The relative cost differential will incentivize fleet operations, which can realize higher utilization rates, and thus lower costs per mile.

As per-mile costs decrease, travel will increase. This will be true for passengers (particularly as part of shared vehicles) but also for vehicle miles traveled since the ability to carry out other activities while traveling will provide incentives for longer commutes or for vehicle travel rather than short-haul airlines.

What might these changes mean for actuaries and the insurance industry? Since Driverless vehicles will most likely be available only to fleet operators and not the general public, their actuarial and insurance implication will differ substantially from the implications of Safe and Self technologies that will be on vehicles purchased by consumers. But, will these vehicles continue to be insured in the same way as personal vehicles are today or will this practice change in some way. For example, if the burden of liability shifts to the technology rather than the driver, then should actuaries focus on product liability rather than personal liability? To what extent does technology rather than personal behavior or demographics become the important link to liability?

Appendix A

Cross-reference to Other Classification Schemes

In the United States, the Society of Automotive Engineers (SAE) and National Highway Traffic Safety Administration (NHTSA) each developed driving automation classification schemes and organized its own vehicle safety systems and technology in the context of driver responsibilities. In 2016, the NHTSA and SAE standardized their systems and technology on the SAE scheme. In addition, the Association of British Insurers (ABI), while not proposing a separate classification system, has separated SAE levels into two groups: Assisted, corresponding to SAE levels 1 through 3, and Automated, corresponding to SAE levels 4 and 5.²¹

The SAE classification framework levels and the market-based definitions defined in this paper do not always align directly, but in the interest of providing a rough guide to the existing framework and its general relationship to these market classifications, the two methods are summarized in Table A1.

Table A1
CROSSWALK BETWEEN SAE^{a, b} AND MARKET-BASED LEVELS OF DRIVING AUTOMATION

SAE/ NHTSA Level	Name	Narrative Definition	<i>DDT: Sustained Lateral and Longitudinal Vehicle Motion Control</i>	<i>DDT: Object and Event Detection and Response (OEDR)</i>	<i>DDT Fallback</i>	<i>Operational Design Domain (ODD)</i>	<i>Market-Based AV Classes</i>
Driver performs part or all of the dynamic driving task (DDT)							
0	No driving automation	The driver's performance of the entire DDT, even when enhanced by active safety systems.	Driver	Driver	Driver	n/a	Safe
1	Driver assistance	A driving automation system's sustained and ODD-specific execution of either the lateral or the longitudinal vehicle motion control subtask of the DDT (but not both simultaneously), with the expectation that the driver performs the remainder of the DDT.	Driver and system	Driver	Driver	Limited	Safe
2	Partial driving automation	A driving automation system's sustained and ODD-specific execution of both the lateral and longitudinal vehicle motion control subtasks of the DDT, with the expectation that the driver completes the OEDR subtask and supervises the driving automation system.	System	Driver	Driver	Limited	Safe-self transition
Automated driving system (ADS/"system") performs the entire DDT (while engaged)							
3	Conditional driving automation	An ADS's sustained and ODD-specific performance of the entire DDT, with the expectation that the DDT fallback-ready user is receptive to ADS-issued requests to intervene, as well as to DDT performance-relevant system failures in other vehicle systems, and will respond appropriately.	System	System	Fallback-ready user (becomes the driver during fallback)	Limited	Self
4	High driving automation	An ADS's sustained and ODD-specific performance of the entire DDT and DDT fallback with no expectation that a user will respond to a request to intervene.	System	System	System	Limited	Driverless
5	Full driving automation	An ADS's sustained and unconditional (i.e., not ODD-specific) performance of the entire DDT and DDT fallback with no expectation that a user will respond to a request to intervene.	System	System	System	Unlimited	Driverless

Notes: a. Based on SAE J3016, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, released September 2016. b. The SAE's driving automation levels are descriptive and informative, rather than normative, and technical rather than legal. Elements indicate minimum rather than maximum capabilities for each level. In this table, *system* refers to the driving automation system or automated driving system (ADS), as appropriate.

Endnotes

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