Automated, Connected, and Electric Vehicle Systems

Expert Forecast and Roadmap for Sustainable Transportation

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Preface

An ongoing study sponsored by the Graham Sustainability Institute at the University of Michigan takes the position that the transportation system should enable individuals to meet their basic access needs safely and in a manner consistent with human health and ecosystem sustainability within and between generations. This report describes the history of road transportation in the United States and the legacy of infrastructure investments in an automobile-oriented culture and presents a roadmap for sustainable transportation based on innovations in connected, automated, and electric vehicle technologies. The infrastructure history is the foundation for applications of forthcoming robotics and communications technologies that support vehicle automation

This roadmap to sustainable automotive transportation takes a cyber-physical sys-ems approach to exploring disruptive innovation in the pursuit of clean, safe, and efficient door-to-door mobility in the United States. This integrated assessment addresses the results to an expert forecast on vehicle automation as part of a more far-reaching transformation to connected, automated, and electric vehicles. The expert panel used the Delphi survey method to forecast the market introduction dates, general growth rates, and policy issues of automated shuttle, freeway, urban, and taxi systems over the course of the next three decades. The results are summarized in a scenario for the growth of vehicle automation in the context of persistent road network, land use, population, climate, and technology trends.

This report explains the goals and objectives of our ongoing expert forecast on connected, automated, and electric vehicles and their potential for contributing to sustainable mobility in the United States. Vehicle solutions like first-and-last mile electric vehicles, self-driving commuter vehicles, and V2I demand management should augment and motivate creative use of the legacy infrastructure in ways that strengthen communities as well as increase worker productivity while improving safety and ultimately ensuring a sustainable mobility in United States. The purpose of this integrative assessment is to investigate these alternatives more completely and to forecast what features of the design will most likely become part of the mobility solution. The expert survey was designed to forecast the future of automated and connected vehicles addressing three levels of automation (1) limited, (2) conditional, and (3) full, over a period of years. The forecasts describe the market introduction of specific systems including automated commuter vehicles, automated first-and-last mile vehicles, full urban (and highway) vehicles that can take the rider to most places without a human driver, and the driverless taxi (or delivery vehicle) that can travel to most places without a human onboard.

While the survey described in this report engaged engineering and research experts primarily from the automotive industry, the intended audience is the policy community including public officials from the state Department of Transportation as well as officials from the Metropolitan Planning Organizations. it is for this reason that while the topic is technical in nature the presentation of the material from the survey is more of a non-technical review of the subject. We have attempted to describe the technical challenges in non-technical terms.

The findings for this project are summarized in a series of charts at the end of the report laying out a timeline of forecasted dates for market introductions of a range of automated vehicle functions as well as forecasts of connected vehicle market growth, period of testing and certification assuming this completed before market introduction, and a generalized forecast taken from the literature on roadmaps for electric vehicles. All of this information is summarized in a single chart at the end of the report that and it is intended to serve more as a straw man to help establish engineering and policy priorities as well as provide a foundation for future surveys on this and related topics.

Some of the findings from our survey and integrated assessment of sustainability include levels of consensus on forecasts for freeway automation and automated shuttle services and pedestrian zones within the next five years. The transition to failsafe freeway automation and freight platooning will involve advances in downloading digital map databases in support of accurate navigation and localization in GPS denied areas. It will take about 10 years before we see self driving vehicles with high levels of automation in urban areas and will be at least 15 years before we see something like an automated taxi or show for service, although, there is much less consensus on the dates for high automation in urban areas and full automation of self driving vehicles. In the meantime we will see steady advances in active safety and driver assist technologies accompanied by increasing levels of market penetration of vehicles with both sensors and drive by wire capabilities. All of this will require comprehensive testing and validation. Higher levels of automation will also be supported by increasing improvements in driver assist technologies and steady increases in traffic safety. All the control technologies for automated and connected vehicle systems will increase safety and mobility. The primary thrust for sustainable transportation will come from the study improvements electric vehicle technology including infrastructure for direct and inductive charging. One of the key findings of our study relates to the potential for precise automated control of vehicle maneuvers to optimize inductive charging and stationary positions as well as the possibility of continuous inductive charging on dedicated lanes of the freeway. Another important finding is the role of telematics to support automated road pricing and demand management to offset the decrease in revenues from gasoline taxes as well as the potential for increasing travel demand from safer and more convenient automated driving, especially offsetting the potential increase in demand from automated freeway driving.

In summary, we believe that policy community remains largely unaware of the pace and extent of the innovative and disruptive technologies that form the core attributes of smart, connected, autonomous electric vehicles. We also believe that the combination of these disruptive technologies is more powerful than implementing each one separately. In order to optimize the combination of technologies and approaches, there needs to be an integrated assessment and close coordination between the public and private sectors in the design and testing of these concepts in comprehensive real-time community pilot demonstration projects. The purpose of this report is to identify the research and policy challenges associated with the vision of an automated connected and electric vehicle and share this with public officials to enable a more informed dialogue on the future of road transportation in the United States.

Special thanks to Steven Marshall and John Niles from CATES who helped with the original concept of this project and helped organize meetings with interest groups in Seattle along the way. I also want to acknowledge Mohammad Poorsartep who managed this project in the first year and went on to greater things in as a project manager at Texas Transportation Institute. Finally I want to acknowledge the help provided by Jane Lappin, Steve Shladover, and Bob Denaro who helped with the initial presentation of the results to the Automated Vehicle Symposium in San Francisco and helped craft the questionnaire for this audience. Mary Doyle, Carolyn Taylor, and James Sherman helped organize the SAE Convergence 2014 survey and invited the attendees to participate.

Introduction

The automobile revolutionized human mobility and combined with the advent of the assembly line and the Interstate highway system provided low-cost transportation to nearly everyone living in the Unites States. From its inception the automobile has remained largely under the control of the human driver with some modest extensions enhancing the vehicles response in braking and handling. In recent years advances in microprocessors, computers, sensors, communications, and battery electronics have started a transformation in vehicle design and the full potential is yet to be realized. Current developments include automated control systems with a range of functionality from vehicle dynamics (e.g., ABS, traction control) to the support of trip planning, route selection, waypoint finding, trajectory planning, and actuation of braking, throttle, and steering (Bengler, et a;. 2014) Engineers are designing systems to assist the driver in potentially unsafe environments, relieve the human driver in mundane driving situations, and to assume full control of the vehicle with the prospect of increasing safety while enabling the driver to attend to things other than driving.

Surface transportation in the United States is a mixed blessing that connects and provides access to people and goods and services across the nation and comes with a legacy of road infrastructure that favors continued investment in automotive transportation. Much of the existing transportation infrastructure in the United States, and especially the interstate highway system, was developed with an emphasis on economic vitality and safety with less consideration given to long-term costs including social and environmental externalities. These developments focused more on expanding highway capacity than on improving operational efficiency, addressing demand management, or planning the integration of transportation with surrounding communities. This study takes the position that the transportation system should enable individuals to meet their basic access needs safely and in a manner consistent with human and ecosystem health within and between generations. It should be affordable; it should operate efficiently; and it should be agnostic to modal and technological preferences. This accessible, safe, and secure transportation system should also support economic vitality in an affordable and cost-effective manner that includes consideration of external costs like environmental and social impacts.

Automotive transportation and the Interstate Highway System in the United States sprouted from post war interests in economic vitality and safety with little consideration given to long-term environmental consequences. Climate change was of no concern through most of the construction of the Interstate. However, now we know that the automobile is a critical force in the In warming of the planet. In November of 2014 the Intergovernmental Panel on Climate Change (IPCC) published its latest Synthesis Report, summarizing the scientific research on the causes and impacts of global warming, and how we can mitigate its consequences. The report concluded that humans are causing rapid and dangerous global warming saying, "Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems. Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen." (IPCC, 2014) From the perspective of the transportation community this is a serious problem because over 50% of oil use around the world is for transportation and three quarters of this is consumed on the roads. Furthermore, IEA Energy Technology Perspective (IEA, 2014) projects that without strong new policies road transportation energy use will double between 2015 and 2050. This trend needs to be reversed and strong international agreements on climate change will be required to make this happen. The IEA vision has industry and governments attaining a combined EV/PHEV sales share of at least 50% of LDV sales worldwide by 2050. This requires electric vehicles to become cost-competitive and along with providing adequate recharging infrastructure.

In their book Reinventing the Automobile, Mitchell, et al. (2010) propose a "new DNA" for the automobile that envisions vehicles that are electrically driven, powered by electric motors, energized by electricity and hydrogen, electronically controlled, and intelligently interconnected with the goals of a sustainable future with zero emissions, renewable energy, crash avoidance, safe social networking while driving, autonomous driving (as an option), varied designs, shorter, more predictable travel times, space- and time-efficient parking, increased roadway throughput, quieter cities, safer pedestrians and bicyclists, more equitable access, and lower cost. While many of these systems still keep the driver engaged the early forms of automation include electronic stability control, lane departure warning, adaptive cruise control, lane keeping and centering, pedestrian detection (day/night), self-parking, traffic sign and signal detection, and vehicle-to-vehicle communication. Taking a more long-term perspective on innovations in transportation Arup (2014) provides a stimulating vision of the future transportation technologies including driverless vehicles, drone delivery systems, driverless car interiors, solar roadways, coordinated traffic signals, dynamic highway, automated bicycle storage, self-healing concrete surfaces, smart cars and vehicle-to-vehicle communication, and automated space-saving car parks. It seems like the possibilities are limitless in a future with robotic sensing, planning, and actuation that replaces the human driver. The question is what innovations do the experts in these fields really expect to see and when? Furthermore, how are these advances going to play out and what sort of policy measures need to be in place to support advances in these areas?

The disruptive solution to sustainable automotive transportation is the integration of electric, automated, and connected. Connected Vehicles offer wireless communications technology to provide additional safety features to both the vehicle and driver. The U.S. DOT defines a connected vehicle specifically as one that can transmit and receive Basic Safety Messages (BSMs) following the WAVE protocol, established in Standard IEEE 802.11p which uses the ITS band of 5.9 GHz (5.85 – 5.925 GHz). They can transmit and receive BSMs and thereby acquire 360-degree situational awareness of other connected vehicles, infrastructure and pedestrians that may create potential crash situations including, for example, oncoming vehicles in two-lane passing situations), oncoming traffic at left turn locations, or vehicles on a collision course at approaching intersections.

Automated driving systems offer a full range of potential advantages over human driving starting with general relief from the driving task and the related stress, boredom, and fatigue associated with driving, not to mention the additional time made available by the automated chauffeur that the rider can use for entertainment or productivity or whatever alternatives can be done while in the vehicle. The increasing demand for mobile media could play a significant role here. The goal would be to design automated driving systems that would drive better than a human driver who is prone to errors from distraction and eyes away from the road. So presumably the automated driving system would have fewer crashes with positive impacts on public health and reduced insurance costs. Another important feature that is not often addressed is the increased precision of the automated driving system enabling relatively simple maneuvers like parallel parking and more demanding maneuvers like backing a trailer up to a dock, adjusting speed to reduce fuel consumption and emissions, fuel efficient vehicle platooning, or possibly guiding the vehicle over inductive electric charging stations. The fully automated driving system may eventually provide increased mobility for the mobility disabled or deliver the vehicle to parking or to the next rider if the vehicle is shared.

The Graham study calls for assembling a panel of experts on automated, connected, electric vehicle technology from both the engineering and policy communities. The study will look for solutions that maximize the efficient use of existing transportation infrastructure that optimize net individual and social benefits associated with alternative modes by improving inter-modal connections, sharing vehicles, and reducing crashes and delay associated with incidents. But fundamentally this study will focus on the redesign of the automobile to attain the vision of a transportation future characterized by intergenerational sustainability.

While this report focuses on the future of telematics, connected vehicles, and automated vehicles the Graham study includes a forecast of electric and hybrid electric vehicles. Another paper addresses the sustainability prospects of electric motors for propulsion and the storage of electricity.

Finally, this study will take into account the tragedy of the commons associated with the nonexclusive use of road infrastructure, the externalities associated with emissions and travel demand management, the difficulties associated with balancing the current and future values of natural resources. More specifically, the goal of this Integrated Assessment (IA) is to investigate short, medium, and long-term technical and policy solutions that will support the design of automated, connected, and electric power automotive solutions that are injury free and accident free, healthy, relaxed, efficient, and productive, and do not discriminate with regard to age and health. Whenever the discussion addresses state and local considerations the states of Michigan and Washington will be used for case study. Our intent is to involve planners from Seattle, Washington to provide input on the local planning considerations addressed in the study.

The key policy question we are focusing on in this integrated assessment: Given apparent trends for innovative, disruptive applications of technology to improve how automobiles serve personal mobility and interact with the environment, what public policies are needed to stimulate technology improvements and other conditions by which cars will enhance their contribution to community livability and sustainability?

Prospects for Future Technology

While the technology for personal urban mobility is available today the transition to networks of lightweight self-driving connected electric vehicles in the United States is wicked because of the infrastructural legacy and institutional momentum supporting the mostly petroleum-fueled, non-communicating automobiles of today. The end we have in mind is a new personal urban mobility system without air pollution, nonrenewable energy consumption, deaths, injuries, wasted time and congestion.

Our survey was designed to help us construct a roadmap on how the vision will be attained, identifying research and development priorities, as well as, identifying milestones and forecasting dates along the way. The survey addressed both technological and policy milestones related to our connected, automated, and electric vehicle vision. Components of this advanced vehicle system include:

- Sensor technology for on-board sensor systems, which are able to deliver accurate and reliable information about the vehicle's environment including moving obstacle and pedestrians in any light, weather, and road conditions.

- Perception algorithms that use information obtained from on-board sensor systems and enable the reliable detection and recognition of relevant traffic features, such as traffic signs, curbs, obstacles, pedestrians, vehicles, etc.
- Localization technology is crucial for path planning and decision-making. On the base environment the use of localization methods based on global positioning systems (GPS) and differential GPS (DGPS) along with inertial navigation (INS) may be sufficient. However, in the continued development of the vehicles at Fort Bragg it will be helpful to adapt an on-vehicle approach independent of GPS that matches a map of the area to the sensed environment to determine the vehicles precise location in the context of the map.
- Communication technology that enables reliable exchanges of information between autonomous vehicles (vehicle-to- new application area vehicle, V2V), but also between the infrastructure and vehicles (vehicles-to-infrastructure, V2I). Communication helps the soldiers to track their vehicle and enables cooperation between vehicles, and is relevant for improving the efficiency and safety of autonomous vehicles.
- Low-level vehicle control includes the control of actuators for steering angle, accelerator, brakes, gearbox, etc.
- High-level vehicle control such as real-time decision-making, and the execution of driving maneuvers.
- Electric motors, battery power, and supporting charging or swapping capability along with electric grid and inductive charging on dedicated lanes of the freeway

The forecast centers on forms of conditional or limited automated vehicles some of which are legally and physically limited to specific geographic areas, for example, last-or-first-mile vehicles that use separate infrastructure or are bound to a gated area like a campus, or vehicles that have been designed for automated driving on the highway where the vehicle is self-driving from entrance to exit. The last-or-first-mile vehicles are distinct in that they offer mobility improvements like better access to transit for the mobility impaired. Similarly, the commuter vehicle is distinct in that it offers unprecedented productivity or free time while the rider is on the highway. The forecast also addresses fully automated or self-driving vehicles that are designed to carry passengers from the beginning to the end of their trip whether the vehicle is owned by the passenger or whether it is shared like an automated taxi. Perhaps the key distinction of the fully automated vehicle is that it can provide single mode transportation, like a taxi, for the mobility impaired.

All of these vehicles at the higher levels of automation must also have high levels of functional safety. In addition, since the driver can attend to other activities it eliminates the concern of distracted driving and it creates a new market of former drivers who now want to be "distracted" whether it is by email or other office and productivity products or whether it is a new market for consumer electronics or digital entertainment.

A secondary impact of freeing these former drivers from the stress of traffic and offering more interesting alternatives is that their time in the vehicle, whether it is a commute or even a shorter ride, is less likely to be unpleasant or possibly even productive or entertaining, and this may increase travel demand. It is not difficult to imagine people being willing to locate their homes further away from work and other locations if their travel time is less stressful, more interesting, or actually productive. So, automation may increase traffic congestion. This concern brings us back to the connected vehicle and the opportunity it provides to manage travel demand through road pricing and market forces and essentially requiring the traveler to pay the marginal cost for their trip on the road network. Will the increased travel demand caused by automation technology be managed by connected or telematics technology?

Professional organizations that that have featured these types of automated systems in the conferences and workshops include, for example, the Association for Unmanned Vehicle Systems International (AUVSI) and the Ground Vehicle Systems Engineering and Technology Symposium (GVSETS).

Adopting a Vision: Disruptive Innovation

As Mitchell, Borroni-Bird, and Burns (2010) point out on page 194 of their book "Reinventing the Automobile", transforming personal mobility is certainly a "wicked problem." Quoting these authors, "*It involves a system of highly interdependent systems, with the property that actions taken to improve one aspect of the system may produce unexpected reactions and unwelcome side effects. It is complex, ambiguous, and defies any straightforward progression from defining goals, through designing and engineering solutions, to manufacture of products and integration and deployment of systems. It is not like getting a man to the moon. It requires creative speculation about possibilities, ongoing critical discussion of principles and options, engagement of stakeholders with differing and perhaps conflicting interests, and responding flexibly to the unexpected twists and turns that emerge along the way to a solution."* In other words, assessing the future of personal mobility is a perfect target for Integrated Assessment as described in this report.

The Integrated Assessment applies a modified version of the Delphi methodology for the purpose of bringing together several communities of experts on future technological developments in sustainable automotive transportation. The Delphi technique originated at the RAND Corporation in the late 1940s is a systematic method for eliciting expert opinion for technology forecasting. It is essentially a method for structuring communication among experts on a selected topic, in this case future innovations in automotive engineering related to sustainable transportation, and to facilitate structured group communication among the experts and ultimately present their concurrence on forecasts related to this topic. The three essential features of the Delphi forecasting process are anonymity of the panelists, statistical summaries of the response, and iterative polling of the panelists with feedback. The Delphi technique generally has the following characteristics: email and web-based questionnaire, questions about both quantitative and qualitative scales, easy to understand instructions for the panelists, statistical feedback with each iteration measuring central tendency, some verbal feedback with each iteration, anonymity of the expert panel, written justification for outliers, iteration of the process until panel reaches a "consensus," and the participants do not meet or discuss these issues face-to-face.

Vehicles are now being equipped with several new technologies to reduce driver errors leading to accidents. These technologies are the precursors to truly autonomous vehicles in which the driver only needs to specify the destination and arrive safely. Fully autonomous vehicles may arrive as soon as 2020, with the potential for an 80% reduction in motor vehicle accidents. Autonomous vehicles will decrease urban congestion and reduce pollution caused by stop and go driving by increasing road capacity without the need to build more lanes. Autonomous vehicles traveling safely at close intervals can triple the capacity of existing highways.

Perhaps the best presentation of an integrative idealized redesign of the automobile is presented in the book Reinventing the Automobile: Personal Urban Mobility for the 21st Century (Mitchell, et al., 2010) where the authors provide a vision for a new automobile era with vehicles that area green, smart, connected, and fun to drive. Their idealized design for the automobile is a vehicle that is

- Safer because the "smart" automated vehicle systems enables the vehicle to drive itself and avoid crashes,
- Smaller because a safe crashless vehicle also required less fuel, produces fewer emissions, and is easier to park,
- Connected because wireless communications enable vehicles to communicate with other vehicles and the roadside to coordinate the flow of traffic and inform and entertain the passengers, and
- Takes advantage of alternative fuels including electric.

The authors take into account the convergence of three major trends – growing urbanization, the electrification of energy and mobility systems, and the ongoing digital revolution in telecommunications and information processing, and bring them together in a comprehensive vision not only for vehicles, but also for personal mobility systems that support sustainable urban patterns.

First, they explain, as summarized in the figure below, today's cars and trucks are primarily mechanically driven, powered by internal combustion engines, energized by petroleum, controlled mechanically, and operated as stand-alone devices. Using the analogy of DNA, they explained that automobiles today essentially have the same "genetic makeup "as the automobile pioneered by Henry Ford over a century ago. The new automotive DNA is created through the marriage of electric powered and connected vehicle technologies. It combines the design of electric motors for power, electricity and hydrogen for fuel, and electronics or telematics for control. The new automotive DNA also supports vehicles that communicate wirelessly with each other and with the roadway infrastructure. When combined with GPS and digital maps the Smart cars know precisely where they are relative to everything around them with a degree of accuracy sufficient for crashless and self driving vehicles. The safer vehicle can become lighter and more economical to power by electric drive.

Second, the mobility Internet will do for automobiles what the Internet has done for computers. Mitchell, et al (2010) adopts lessons from the evolution of the Internet where the large-scale networks combined with powerful and inexpensive smartphones produced economies of scale and drive down the price of access. They make the case that personal urban mobility of the future will be smaller and draw on similar economies of scale. They also explain that the smartphones and other devices provide access to appealing new services that motivate more widespread adoption. Similarly, the personal urban mobility networks provide increased safety, enhanced mobility, and better air quality and this all comes at a lower cost. Like the TCP/IP and HTP standards for the Internet and the Web, the personal urban mobility systems will have open standards that encourage bottom-up development and interoperability of components and vehicles. Finally, the early public-private investment partnership for the Internet through ARPA, NSF, etc., brought the Internet startup up to the point where the positive network externalities generated growth and pervasive adoption. Similarly, their personal urban mobility network needs some initial large-scale investments, but once it gets going the smart electric self-driving vehicles will create their own demand while exploiting their synergies with smart grids and providing riders alternatives to the active driving task.

Third, they take it a step further and combine electric drive vehicles with energy-efficient buildings and smart utility grids to create distributed, responsive energy systems. The systems will support the use of diverse and renewable sources of electricity. Furthermore, because electricity and hydrogen are interchangeable and hydrogen can store energy more densely than batteries, they conclude that smart energy systems will enable the optimal next of batteries and fuel cells to facilitate both stationary and vehicle uses electricity.

Fourth, the capstone of their idealized design is the electronically managed, dynamically priced markets for electricity, roads, parking, and vehicles. While these markets are underdeveloped today the new technologies for electronics and connectivity can help realize their potential. These cyber physical systems depend on ubiquitous metering and sensing and use centralized servers to evaluate prices and provide incentives to regulate supply and demand. Their conclusions can be summarized in four ideas.

Table 1. Automobile DNA

Current DNA	**New DNA**
Mechanically driven	Electronically driven
Powered by internal combustion engine	Powered by electric motors
Energized by petroleum	Energized by electricity and hydrogen
Mechanically controlled	Electronically controlled
Stand-alone operation	Intelligent and interconnected

They make the case that it will take an idealized integrative design combined with sustained public and private investment to get beyond the inertia of scale and codependency on fuels, roads, and tax revenues inherent in the automobile transportation system. Again, they use the analogy with the communications industries where the Internet and PCs burst onto the scene where the telephone, radio, television, newspapers, and book publisher industries had a heavily regulated and vested interest. They describe it as a "wicked problem" involving a system of highly interdependent systems where pro-active solutions in one system can cause unexpected and unwanted reactions in another system, and where it help to engage in "idealized design," that is, starting with the desired end in mind and then working backward to where you are today to develop a roadmap to your destination. (Ackoff, et al., 2006); in this case the idealized design is self-driving, connected, and electric.

Burns (2013) summarizes the building blocks for this vision of our transportation future. Connected vehicles will include both long-range telematics and short range vehicle-to-vehicle, vehicle-to-infrastructure, and vehicle-to-x communication and connectivity to the digital cloud. Coordinated vehicles use the vehicle-to-infrastructure and cloud connectivity to manage the movement of people and goods through the transportation network. Shared vehicles will have a range of alternative ownership and payment arrangements to enable multiple riders to engage in continuous or optimal use the vehicles throughout the day. Driverless vehicles will emerge from the evolution of automation starting with driver assist and advancing to freeway and finally urban autonomy. all of this serves to optimize the movement of electric vehicles powered with electric motors and digital controls to reduce emissions in the longer term. The final building block identified by Burns is the tailored vehicle that is designed specifically to accommodate lower speeds fewer passengers for shorter trips within the city.

Remainder of this report goes into more detail on research issues for automated vehicle system in the larger context of the impact of disruptive technologies on sustainable mobility. At the level of large-scale cyber-physical systems we address integrative system design, wireless connectivity, and Cybersecurity. At the level of vehicle systems we address sensing and perception, behavior planning, machine learning, and the interface with the human operator. We then address the design issues of adaptive graceful degradation, vehicle and capability prototyping, and testing, evaluation, validation, and verification. Some of the findings addressed in the section are the results from an earlier survey of autonomous vehicles (Underwood, 2012). Most of the findings in this section are from responses to the current survey.

Project Motivation/Purpose

The economic and social functioning of the U.S.A. is heavily reliant on personal vehicle ownership and use. However, relying on motor vehicles for personal transportation beyond walking distance is associated with a number of problems: low density land consumption; air and water pollution; traffic congestion; accidental death and injury; sedentary unhealthy life styles; inequitable access to services and opportunity by those without a car; road infrastructure construction, operation and maintenance expenditure requirements beyond public willingness to pay.

In light of these problems, many leaders and professional experts in transportation have begun to promote the Smart Growth model where the focus is shifted from single occupant personal automobile use toward walking, bicycles, transit, and various configurations of car sharing and ride sharing. Smart growth policies tend to reduce per capita impervious surface area (land covered by buildings or paved for roads and parking facilities), vehicle ownership and vehicle travel, and increase use of alternative modes compared with more dispersed, automobile-dependent, sprawled communities (Litman, 2012). However, forecasts of future consumer travel demand outside of the New York City metro area continue to have 90 percent and higher trip market shares forecast for cars overall in the coming decades even after considerable policy and budget focus to encourage denser patterns of land use and greater investment in and use of public transit. An example is the Seattle-Tacoma regions, where 95 percent of vehicle trips are forecast to be in cars even after spending billions on new rail transit and smart growth (Puget Sound Regional Council, 2012). Fortunately, the automobile, coupled with installed communication technology and new kinds of power plants, is morphing into a more sustainable means of movement where the mentioned problems could be mitigated rather considerably while still offering the same level of convenience and comfort of door-to-door transportation that has been desired by the public over the decades since World War II.

This project frames several conspicuous problems associated with today's automobiles, engages stakeholders in an investigation of the emerging technologies and the impact they could have on those problems, and explores a future roadmap where technology is applied to overcome problems. A global perspective has been maintained throughout the scenario building exercise regarding technological improvements changes with impacts on U.S. The process has employed an Integrated Assessment methodology to evaluate the implications for sustainability and livability of the evolving automobile.

The word "disruptive" is used because current government planning activities have not yet come to grips with all the policy implications and sustainability implications of the battery-powered, non-polluting electric cars that are emerging from the automobile industry with high levels of computerization, wireless communications, and even automated controls. Such vehicles are on a development path to significantly reduce vehicle and pedestrian accidents while automatically triggering electronic tax/fee payments covering road maintenance and insurance based on daily usage metering. The three Es of sustainability—environment, economics, and equity—are all going be affected.

As a result of Phase 1 planning activities funded by Graham Institute, the research team used an Integrated Assessment process and its results to produce a product addressing these disruptive technologies in sustainable mobility. The model reflects input gathered from the scientific, engineering, and policy community as engaged in the IA.

Expert Survey and Integrated Assessment

To achieve a structured dialog among people coming from different disciplines and policy perspectives, the team has employed an analysis of policy alternatives that features future scenarios for new personal mobility approaches based on critical uncertainties about the development of autonomous, electric vehicles. Scenarios of about one descriptive page each, with further data online for optional deeper exploration, were offered to stakeholders representing the public sector, the business sector, the non-profit sector, and academia for active discussion and improvement through a structured series of policy exercises (Brewer, 1986, Underwood, 1987; Underwood & Toth, 1987) that combine face-to-face and online interaction via a modified Delphi method of eliciting stakeholder input with feedback provided from the other participants. Delphi may be characterized as a method for structuring a group communication so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem. To achieve the desired "structured communication" the process provided feedback of individual contributions of information and knowledge; assessments of the group judgment or view; opportunity for individuals to revise their views; and anonymity for the individual responses. (Linstone & Turoff, 1975)

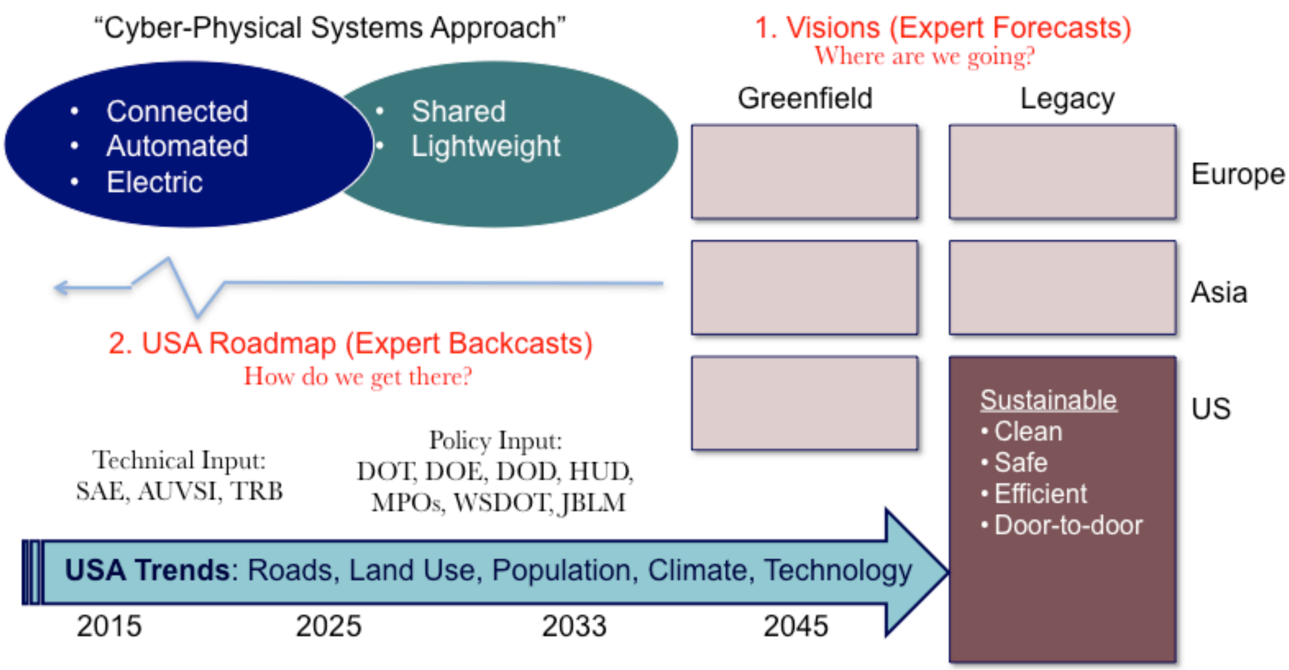

Figure 1. Integrated Assessment Method

Delphi researchers employ this method primarily in cases where judgmental information is indispensable, and typically use a series of questionnaires interspersed with controlled opinion feedback (Rowe, Wright, & Bolger, 1991). A key advantage of the approach is that it avoids direct confrontation of the experts. Dalkey and Helmer observed: [The controlled interaction] appears to be more conducive to independent thought on the part of the experts and to aid them in the gradual formation of a considered opinion. Direct confrontation, on the other hand, all too often induces the hasty formulation of preconceived notions, an inclination to close one's mind to novel ideas, a tendency to defend a stand once taken, or, alternatively and sometimes alternately, a predisposition to be swayed by persuasively stated opinions of others (Dalkey & Helmer, 1963)

The expert survey was conducted in four phases. The first questionnaire asked the panel to construct elements of the vision including preliminary forecasts on automated and connected vehicles that was matched with similar existing revisions on electric vehicles. The literature on electric vehicles is more mature than the literature on automated vehicles so the electric vehicle portion was based on literature review. The first questionnaire was designed to elicit the panel's expectations about technology and social trends related to automated and connected vehicles and to describe how they may play out in support of sustainable mobility in a timeframe of 30 years and beyond. The results of the first survey was summarized and organized into a second set of questions asking about the panelists priorities regarding research and policy and connected and automated vehicles. The second survey helped us to construct a roadmap of policy and technology issues that need to be addressed over time in order to reach the goals set out by the vision. A third questionnaire was developed in order to get the panelists response to a few more additional issues that emerged as well as to reorient the forecasts of market introduction toward the levels of automation defined by the Society of Automotive Engineers (SAE) in their definitions of automated vehicle system (J3016). A fourth questionnaire in order to survey the attendees at the Automated Vehicle Systems Symposium 2014 held in San Francisco in July 2014 and sponsored by the Association of Unman matched the previous surveyed Vehicle Systems International (AUVSI) and the Transportation Research Board (TRB). This last questionnaire was identical to the third questionnaire provided to our panel of experts and was designed as a form of outreach to the scientific and engineering community responsible for research and development of the automated and connected vehicle systems addressed in the survey. Again, the overall intent was to map out a vision and to define a roadmap for arriving at the long-term future of sustainable automotive transportation.

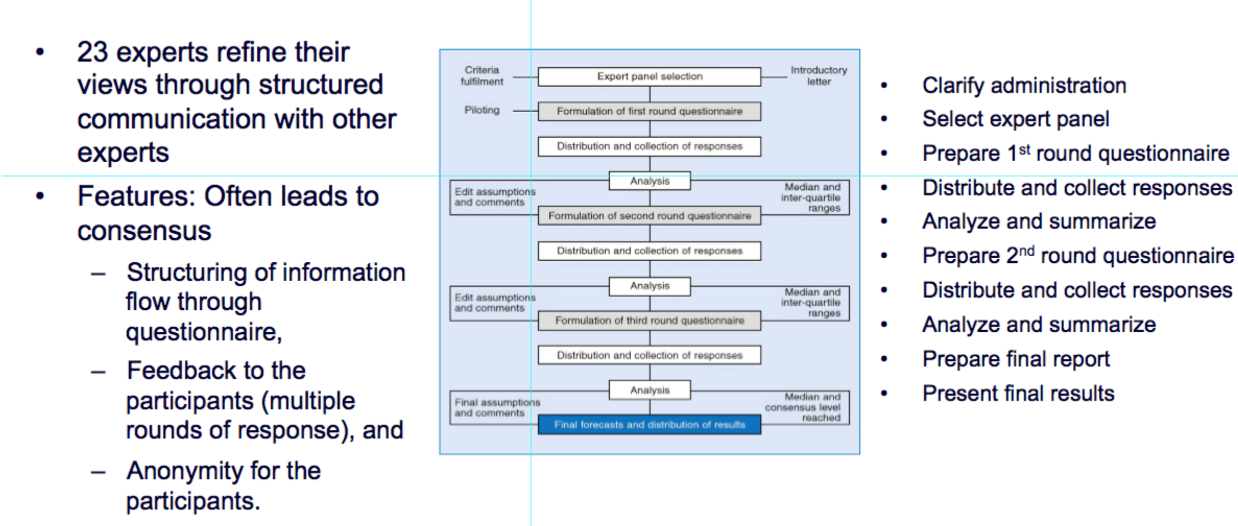

Figure 2. Delphi Expert Panel Survey Process

The panel consisted of 23 experts that were selected through an anonymous election process where the survey team interviewed a handful of recognize experts in the fields of automotive electronics engineering and robotics. The subjects of the interviews were asked to identify three top experts that they would recommend as panelists. This list of potential panelists was summarized and we conducted outreach to these individuals asking them if they would be interested in participating and who would they identify as top experts in the field. We summarize these results and continued through a process of identifying those individuals who cut across the areas of expertise and robotics, systems engineering, connected vehicles, automated vehicles, computer science, sensors, technology policy and planning, automotive business planning, and other areas. Our target was to have a panel of 20 experts and after going through this process we identified 23 individuals who on the average have 11 years of experience with automotive vehicle research and development. Again, the selection process was anonymous and the panelists remained anonymous throughout the survey process.

Automotive Transportation Legacy in the United States

The United States is a quilt-work of continental expanse stitched together through centuries of ambitious earthmoving and investment in infrastructure. From the earliest days of this nation the federal government encouraged the building of critical canals, railways, and roadways to connect the breadth and depth of cities and states. In the 19th century the United States Congress provided funding for the transcontinental railroad linking the East Coast to the West Coast. Then, from 1956 through 1992 the nation constructed the interstate system under the Federal Highway Act. At a direct cost of $128 billion, or $500 billion in 2008 dollars, the national system originally included over 46,000 miles of limited access highway and became the largest and most expensive public works project undertaken in the 20th century (Winston, 2013). The history of highway infrastructure in the United States is part of the transportation legacy that Americans experience today and must manage successfully in the future if sustainable mobility is going to be achieved in the United States.

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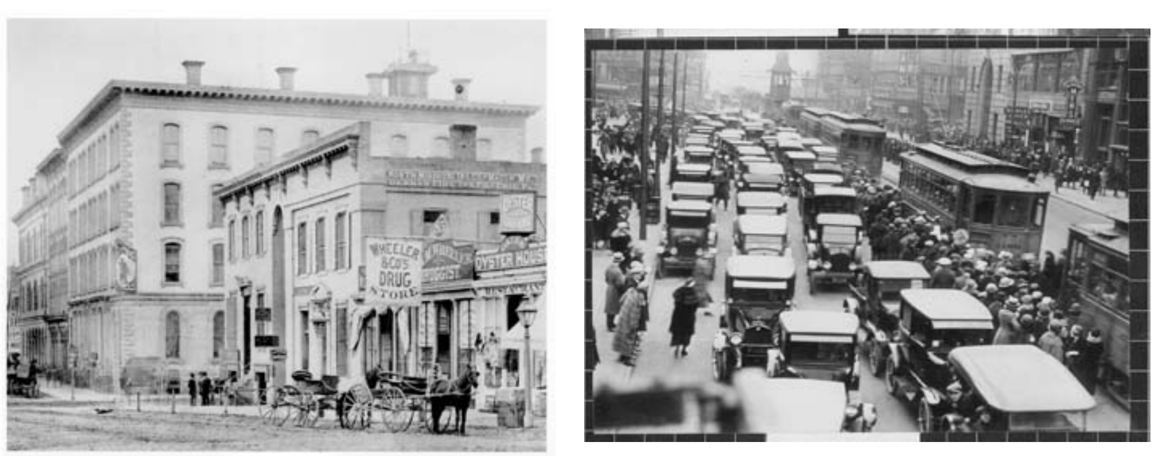


Figure 3. Griswold Street, Detroit Michigan, Automobile and Assembly Line as Disruptive Innovation

Automobile: Disruptive Innovation

Since 1992 the network of freeways has been extended, and as of 2010, it had a total length of 47,182 miles. As a symbol of American freedom and economic prosperity paved, limited-access highway provided the foundation for the automobile to become the dominant mode of passenger transportation in the United States. It was through construction of this National System of Interstate and Defense Highways that the automobile provided Americans with unprecedented levels of individual mobility and access to desired destinations across the United States. For the last 60 years the United States has employed highway construction as a coast-to-coast economic development policy with the purpose of improving access, location choice, and the movement of individuals, firms, and goods; and this has helped America's economy to remain one of the world's largest, and its citizens to be among the richest in the world.

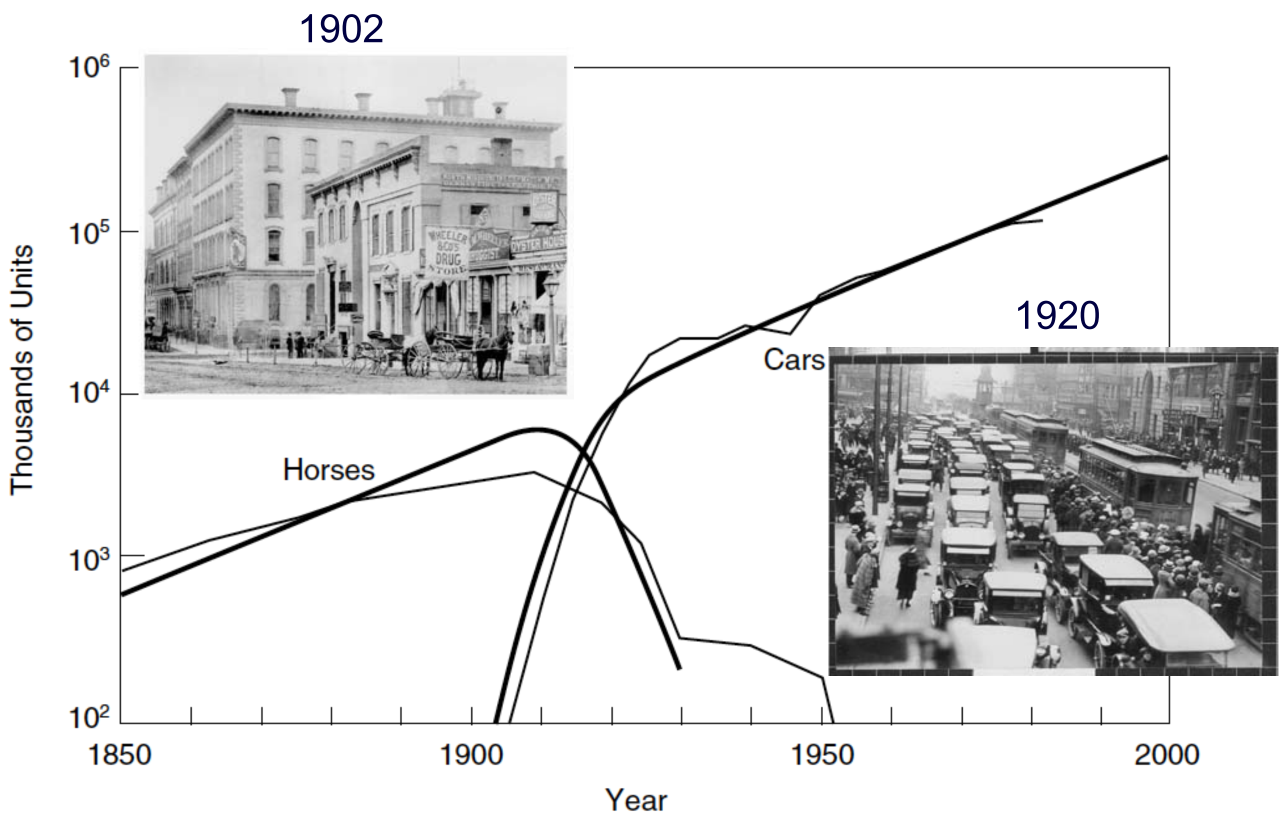


Figure 4. Disruptive Innovation, Nonfarm Draft Animals and Automobiles Nakicenovic, 1986

The early 20th century in the United States saw critical advancements in technology. The US economy received a jolt by the spread of modern electricity, telephones, and the advent of the automobile, which evolved to provide point-to-point connections for people and goods across the nation. The automobile has been a major force in 20th century America serving as the backbone of the consumer goods oriented society in the 1920s and providing one out of every six jobs in the United States by the 1980s. Production line manufacturing of affordable automobiles started as America entered the 20th century and Henry Ford expanded this concept in 1914 with production of the Model T. By the 1920s the automaker were no longer experimenting with design. They placed the engine under the hood and installed cable brake systems, steering wheels, and combustion engines. The number of automobiles produced annually quadrupled between 1946 and 1955.

Urbanization and Suburbanization

The growth of road transportation was a critical underpinning of economic growth in the United States in the later half of the century. The automobile has been the lifeblood of the petroleum and steel industries. Furthermore, the automobile ended rural isolation and provided the foundation for the modern American city with surrounding industrial and residential suburbs. Furthermore, urban Americans could take the car out of the city to escape the dirt, noise, and congestion of city life. Due to government encouragement after World War II, such as the Federal Housing Administration, many families migrated from cities to suburbs. These new middle-class families saw dramatic improvements in their quality of life. They married young, had many children, and adopted a suburban lifestyle. Central to this lifestyle was reliance on the automobile as the predominant means of transportation.

As the highway and road infrastructure of the nation flourished, the design of cities adjusted to requirements of automobiles for movement and space. Buildings were replaced by parking lots. Open-air shopping streets were replaced by enclosed shopping malls. Walk-in banks and fast food stores developed drive-in versions inconvenient for pedestrians. Single function business parks and entertainment complexes replaced mixed commercial town centers. Although the long-term historical trend in the United States is movement of populations from rural to urban areas, suburbanization has led to falling population density. In fact, in the US as a whole, the population-weighted density fell by 16 people per square mile between 2000 and 2010, while in metropolitan areas it fell by 405 people per square mile (Salmon, 2013). All of this favors automotive transportation over other modes. It also comes at a cost of maintaining the road infrastructure. As a consequence, all levels of government in the United States made highway funding a high priority at the expense of other modes of transportation.

The outcome of the automotive culture and highway construction policy in the later 20th century and now in first decade of the 21st century has been mixed. While all cities and urban centers are connected across the nation with high-speed limited access travel corridors, the reliance on automobile transportation, and what some may argue as over-reliance on a single mode, has resulted the physical and political division of urban areas and in suburbanization and other low density land use patterns that produce long commutes and overuse of the highway commons with serious economic, environmental, and social costs. Automakers sold more, than 14 million vehicles in the United States last year, accounting for around 30% of domestic economic growth during the first six months of the year. The overall number of passenger vehicles has increased and surpasses the number of licensed drivers with a total of over 250 million registered passenger vehicles for close to 200 million licensed drivers in 2009 in the United States with a total population of over 300 million at that time.

Automobile Transportation Impacts

Accompanying this unrivaled expansion of investment in automotive transportation were parallel and related trends like increases in automobile crashes, injuries, and fatalities, decrease in use of alternative modes of transportation starting with horse and buggy and extending to decreases in transit usage and availability, and increases in fossil fuels along with related concerns about climate change and global warming. The era of public transit including passenger rail, private bus, and public transportation in general was short-lived in the United States.

Automobile Crashes

Because of the reliance of automotive transportation the average American commuter spends approximately 250 hours on the road, and although the total is decreasing, there are still approximately 15 traffic deaths per hundred thousand population in the United States, or roughly 6 million crashes, 2.5 million injuries, and over 30 thousand deaths per year. Traffic accidents are the leading cause of death for citizens between the ages of four and 34 years of age. According to the Texas Transportation Institute in 2011 Americans living in urban areas wasted about 5.5 billion hours sitting in traffic (Schrank, et al., 2011). They also wasted 2.9 billion gallons of fuel with the total cost of congestion for the average commuter at a level of $818. Moreover, 68.8% of adults in the United States are classified as overweight or obese with 35.7% of them rating obese (Flegal, et al, 2012). Many attribute the rise in obesity to the sedentary lifestyles associated with the automobile culture.

Climate Change

Road transportation is also largely dependent on petroleum as a fuel. The United States is a net importer of petroleum and subject to the fluctuations in the world market price of oil and political instabilities in the oil-rich regions of the world. Roughly 99% of fuels used in road transportation are petroleum-based. Furthermore, the burning of fossil fuels in diesel and combustion engines has an adverse impact on local air quality and worldwide climate change. While the United States automotive industry has made significant progress in designing vehicles with reduced emissions nearly 30% of all CO_2 emissions in the United States are caused by the transportation sectors.

Climate change may be the most influential continuing trend influencing transportation in the United States throughout the 21st Century. This much is clear: (1) global temperatures are rising, (2) sea surface temperatures are rising, (3) glaciers are melting, (4) heat waves and other weather events are becoming more common, and (5) humans are contributing to this through their use of energy products that emit Greenhouse Gases (GHG). These changes come at serious cost in the form of severe weather events, agricultural productivity, and severe changes to our habitat over time. Transportation plays a major role in contributing to and controlling this trend.

In the 20th Century global temperatures have risen between 1 to 1.4 degrees Celsius. Although there was a period of cooling from 1940 to 1970 (Swanson, et al, 2009) along with a hiatus in 1998, and uncertainty exists about the sequencing and timing of events in computer climate models, most researchers believe the earth will continue to warm by 3-10°F over the 21st century.

Warming continues in parallel to increasing Greenhouse Gas emissions into the atmosphere. For example, CO_2 levels were measured at 389 ppm in 2010, which is the highest they have been in the past 650,000 years (NASA, 2010). This and other evidence show that close to seventy five percent of the 20th century increase in the atmospheric greenhouse gas CO_2 is directly caused by human actions like burning fossil fuels. The renewed discussion in the United States on climate change comes on the heels of reports by the national climate assessment and the United Nations Intergovernmental Panel on Climate Change alerting us to the damaging effects of disruptions in our climate and the increasingly dire future predicted by the scientific community. There is a strikingly strong consensus among climate scientists that our planet is warming and that humans are primarily to blame. According to the United Nations National Research Council:

> [T]here is a strong, credible body of evidence, based on multiple lines of research, documenting that climate is changing and that these changes are in large part caused by human activities. While much remains to be learned, the core phenomenon, scientific questions, and hypotheses have been examined thoroughly and have stood firm in the face of serious scientific debate and careful evaluation of alternative explanations. Some scientific conclusions or theories have been so thoroughly examined and tested, and supported by so many independent observations and results, that their likelihood of subsequently being found to be wrong is vanishingly small. Such conclusions and theories are then regarded as settled facts. This is the case for the conclusions that the Earth system is warming and that much of this warming is very likely due to human activities.

Complicating this picture is the United States' roles as a major worldwide contributor to this problem especially on a per capita basis. As of 2009, the US had 4.5% of the world's population but was responsible for about 28% of all global greenhouse gas emissions (USGCR, 2009).

Cost of Automotive Transportation

Finally, if these indirect costs of road transportation are not enough, the car-based transportation systems also have a direct impact on household finances and expenditures. Americans spend about 20% of their household income on transportation and the largest share of this expenditure is associated with owning, operating, and maintaining automobiles. According to AAA in 2014 Americans spent approximately 58.9 cents per mile if they were driving a medium sized sedan and drove 15,000 miles per year or 8,835 dollars per year. This includes fuel, maintenance, tires, insurance, licenses, registration, taxes, depreciation, and finance charges. On the average commuters pay $59 in total vehicle expense every 100 miles.

Historically gasoline has been on the average approximately one third of the total annual cost of owning an automobile and individual impacts depend largely on the total mileage for that vehicle. So, the recent decline in oil and gasoline prices has had a significant impact on the reduction of total cost of automotive transportation to consumers and especially to commuters and fleet operators in the United States. If these low gasoline prices continue, as some expect, this will challenge the growing movement to switch to alternative fuels on the basis of direct costs. For example, if the price of gasoline stays below $2.50 per gallon then the prices of electric vehicle batteries need to approach $200 per kilowatt hour to become completive on the basis if direct costs. This will be challenging and will, at minimum, take many more years to reach a competitive level with gasoline without a policy to internalize the external costs of gasoline or providing a significant subsidy to batteries or other alternative fuels. As the awareness and impact of climate change grows internationally and in the United States this this issues will be addressed.

With regard to road maintenance, total public spending on transportation infrastructure in the United States has decreased steadily since the 1960s and now stands around 2 1/2% of gross domestic product. Funding for both capital investment and operations and maintenance the road infrastructure in the United States has dropped steadily for decades. The Congressional Budget Office estimates that America needs to spend at least $20 billion per year more just to maintain its infrastructure at the present levels. Up to $80 billion a year in additional spending could be spent on projects that would show positive economic returns. The national surface transportation policy and review study commission in 2008 determined that America needs at least $255 billion per year in transportation spending over the next half-century to keep the system in good repair and make the needed upgrades current spending falls at least 60% short of this amount.

Automotive Technology Building Blocks

Redesign of the automobile is part of the mobility solution. In recent years the field of automotive electronics has given rise to several independent and related prospects including telematics, connected vehicles, and automated vehicles. However, these three communities have advanced relatively independently in terms of innovations, professional practice, organizational boundaries, and dialogue with others outside their communities. Furthermore, the government community known as policy or public administration influences all three. So, for example, one could argue, "scientists and policy live in separate worlds with different and often conflicting values, different reward systems, and different languages." (Caplan, 1979) While scientists and engineers are more concerned with pure science and esoteric issues, government policymakers are action-oriented, and practical people concerned with obvious and immediate issues.

A reason for describing the four communities in Figure 2 at a high level of detail is to emphasize the need for systems integration in the future design of automotive electronic systems. The value of Integrated Assessment (IA) in this study is bringing together experts in the three automotive electronics engineering communities and the transportation policy community, creating bridges between these communities. This convergence of technologies and focus on integrated systems engineering is one of the critical paths on the roadmap to develop a fully automated or autonomous vehicle that address the sustainable mobility vision of this project. Envisioning an integrated technical and policy roadmap for the implementation of potentially disruptive innovation in the design of the automated and connected vehicle solution to sustainable mobility was enabled through bridging the three communities working on vehicle electronics, along with the power-train design community as well as the transportation policy and planning communities in the public sector. We conducted the IA in order to promote a unified vision of innovation of automotive electronics and communications technologies that will create new markets for automotive engineering solutions that will let the U.S establish and maintain a sustainable mobility system.

Transportation systems that move people, goods, and services in societies worldwide pose unprecedented environmental, economic, and social challenges, particularly with the growing urgency to conserve energy, cut back on carbon emissions and pollution, avoid crashes, and relieve congestions. Advances in electric vehicle (EV) technology, alternative energy, connected and automated vehicle systems, multi-modal transportation and intelligent transportation systems, offer great promise to address these challenges and have the potential to revolutionize the future transportation systems. However, each of the areas (connected, automated, and electric vehicles) has largely been under development separately, and while researchers around the world are making significant advances in each of areas, there is little work on how to integrate them to create a viable "system" that meets the dynamic needs of a changing society. Only by envisioning the "idealized" design of the connected and automated electric vehicles as a whole and working together to address long term sustainability will we be able to establish the scientific foundations and engineering principles needed to realize a cyber-physical approach to mobility and accessibility that is capable and dependable beyond what can be achieved today.

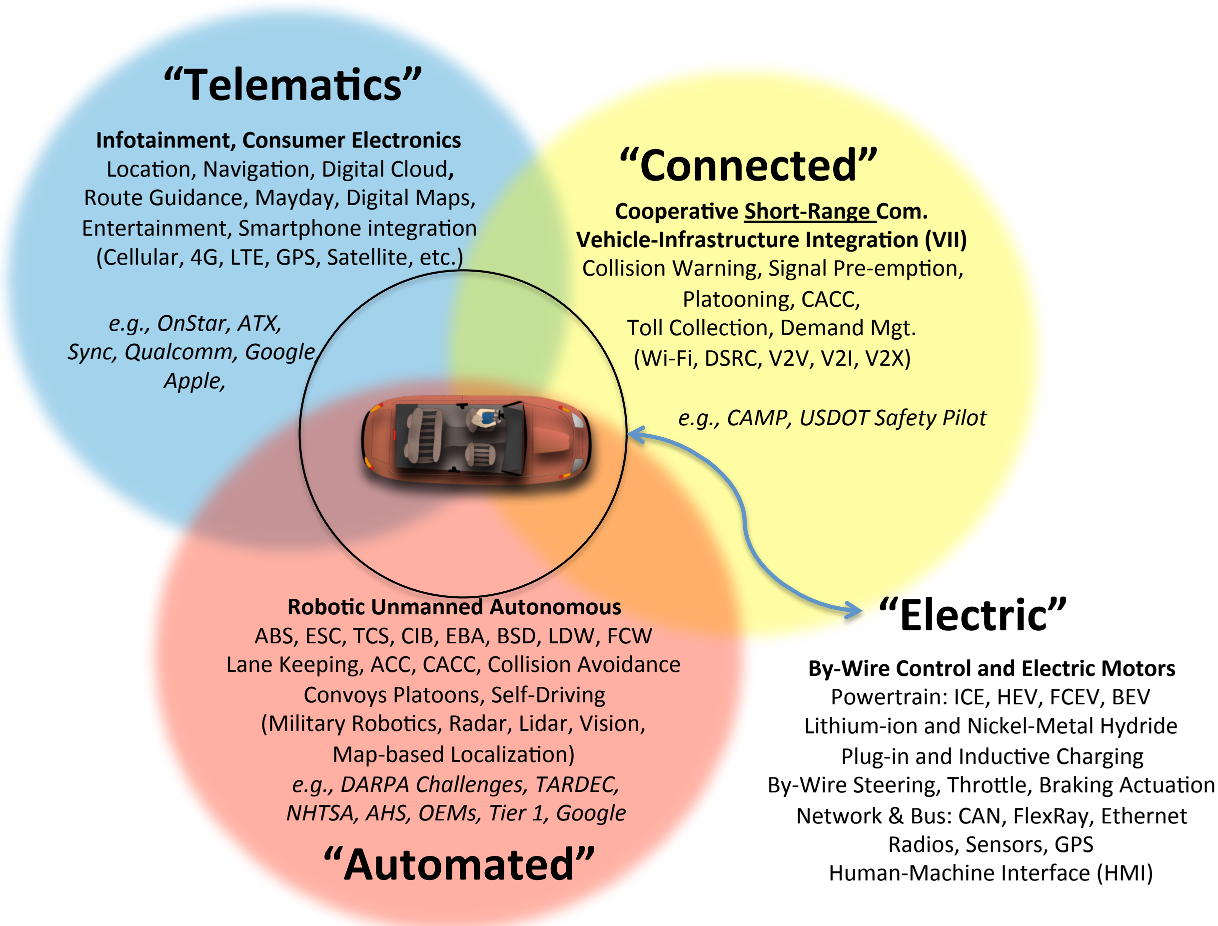


Figure 5. Four Automotive Electronics and Communications Technology Communities

Telematics: Information and Digital Maps

The first of the three communities is what has come to be known as "Telematics" with a focus on infotainment and consumer electronics designed to communicate with the driver and to help in locating, navigating, and guiding the vehicle and the road transportation network. This is relatively mature area automotive electronics engineering and product development that emerged in the 1990s with what may be more recognizable services and name brands including the likes of GM OnStar and Ford Sync. Telematics products are discussed, featured, and demonstrated at professional conferences like Telematics Update, the Consumer Electronic Show, and GENIVI.

The adoption of telematics poses a dilemma for the consumer because while it provides and number of conveniences like route guidance and traffic information it also potentially distracts the driver and poses a serious safety risk. Furthermore, not only does telematics distract but also should an accident occur telematics also offers mayday services that saves lives. However, perhaps the most important telematics product is the digital map that updates continuously for localization and wayfinding in automated driving systems.

Connected Vehicle Systems: Safety and Security

An outgrowth of vehicle communication is a somewhat later development came in the area of what is now known as "Connected Vehicles" that feature short range communication systems between vehicles, that is, vehicle-to-vehicle, or V2V, between vehicles and the infrastructure, or V2I, and between vehicles and others including pedestrians or the cloud, or V2X. Examples of these short-range communication systems include collision warning, signal preemption, platooning, cooperative adaptive cruise control, toll collection, demand management systems like road pricing. The most advanced demonstration of connected safety systems is the US DOT Safety Pilot in Ann Arbor Michigan where 3000 vehicles were outfitted with Dedicated Short-Range Communication (DSRC) to demonstrate safety applications including warnings of potential collisions:

- Blind Spot Warning/Lane Change Warning, which warns drivers when they try to change lanes if there is a car in the blind spot or an overtaking vehicle.
- Forward Collision Warning, which alerts and then warns drivers if they fail to brake when a vehicle in their path is stopped or traveling slower.
- Electronic Emergency Brake Lights, which notifies drivers when a vehicle ahead that they can't see is braking hard for some reason.
- Intersection Movement Assist, which warns the driver when it is not safe to enter an intersection—for example, when something is blocking a driver's view of opposing traffic.
- Do Not Pass Warning, which warns drivers if they attempt to change lanes and pass when there is a vehicle in the opposing lane within the passing zone.
- Control Loss Warning, which warns the driver when another nearby vehicle has lost control.

Yet another connected feature that has market potential is cooperative adaptive cruise control (CACC) with initial applications for fleets and later in passenger vehicles. CACC not only promises to make driving easier while reducing potential crashes but at higher levels of market penetration it promises to smooth out the flow of traffic and increase overall energy efficiency (Shladover, et al., 2012).

One of the most recent issues concerning connected vehicles is the growing competition in the market of sensors for collision warning and collision avoidance. While the safety pilot in Ann Arbor demonstrated the real value of vehicle-to-vehicle communication with a large population of connected vehicles, it did not take into account the potential competition with radar and vision systems. That is, safety benefits of vehicle-to-vehicle communication are likely to be pinched by the growing demand for non-connected safety systems in new vehicles. While some make light of this market threat by pointing to the need for system redundancy, this risk comes to the forefront when taking into account the price and effectiveness of multiple sensor-based solutions, the need for other vehicles to have transceivers in order to communicate, and the years required for getting connected vehicles into the marketplace. It also doesn't help that the digital maps required for higher levels of automation are most likely to be updated by 4G cellular phone technology (i.e., telematics). If left only to the market the short-range communication systems are not likely to have a large role in automotive safety applications or transportation in general. However, should the government decide to mandate, to regulate, or even to provide incentives for connected vehicle technology then the long-term value of V2V as a redundant safety feature with other high-value applications possibilities will be assured.

It is critical to be aware of the potential non-safety applications of connected vehicles. Perhaps more important than safety is the role of vehicle-to-infrastructure (V2I) communication in facilitating the evolution toward the adoption of road pricing as a source of government finance for transportation. That is, the connected vehicle systems that have been tested most recently for vehicle-to-vehicle safety applications will also support V2I automated toll collection applications that can assist with congestion pricing and the collection of user fees that will have the potential to finance a sustainable transportation strategy.

Finally, some of the most promising automated systems from both productivity and environmental perspectives involve cooperative or vehicle-to-vehicle automation including cooperative adaptive cruise control and truck platooning. V2V communication enables platoons to coordinate multiple vehicles simultaneously and avoid issues of latency sequence delays with a result of shorter headways and greater benefits in terms of reduced emissions and greater fuel efficiency. Furthermore, V2V communication support platoon entrance, exit, merging, and other vehicle behaviors that requires two-way signaling between vehicles. It also supports coordination of vehicles with traffic signal timing and crossing traffic at intersections.

While much of the progress in these areas was made available through the conferences of the Intelligent Transportation Society of America, the Intelligent Transportation Systems World Congress, and the Transportation Research Board, much of the academic and engineering progress has been made available through conferences and publications of the Institute of Electrical and Electronics Engineers (IEEE).

Automated Vehicle Systems: Crashless to Driverless

The next generation of active safety systems will prevent crashes by improving the driver's control of braking and steering, warning of potential crashes, and taking over control of the vehicle under certain circumstances to actively avoid a collision. Braking systems are now enhanced to improve steerability, hasten deceleration, and prevent skids and loss of traction. Soon a bubble of sensors and actuators will enclose the vehicle and protect it from crashes. The vehicle of the future will assist with the driver with adaptive cruise control and lane keeping assist. The vehicle will warn the driver of potential crashes and intervene if for some reason the driver does not respond. Even when a crash is imminent the vehicle will take over to limit the impact. Many of these types of systems are on high-end or luxury vehicles today. However, as with most automotive electronics the cost is going down and in the not-too-distant future low-end vehicles will be equipped and some of these features may become standard.

The key point is that a crashless vehicle is not necessarily driverless. Systems are already and will continue to be designed to assist the driver and prevent crashes. The early active safety systems actually assist the driver and improve their control of the vehicle. On the other hand a self-driving vehicle must be designed with high assurance to not crash and these improvements in active safety and driver assist are steps in this direction. Over time as the population of crashless vehicles increases on the roadway it is likely to open the door to more widespread customer acceptance and adoption of self-driving vehicles. Furthermore, since the driver is the primary cause of vehicle crashes as automation technology develops and takes the driver even further out of the control loop, there are additional benefits to be had. For example, if over 40 percent of fatal crashes involve alcohol, distraction, and drug involvement or fatigue, it that may help to find a source of control other than the driver. Looking far enough into the future, this trend toward crashless cars may also reduce the need for passive safety and crashworthiness. In other words, the crashless car can also be a lighter car with reduced vehicle mass and therefore more fuel-efficient.

More recent developments in the "automated" vehicle community have emerged primarily from projects sponsored by the Department of Defense (DOD) with an emphasis on robotic engineering associated with unmanned ground vehicles or what have become known as "autonomous" vehicles. While automation in the automobile can range from automatic door locks to higher levels of automation like the fully automated self-driving vehicle, more recently the Society of Automotive engineers (SAE), the National Highway Traffic Safety Administration (NHTSA), and the Germany Federal Highway Research Institute (BASt) have developed taxonomies of automated driving that define levels of vehicle automation ranging from no automation where the human driver performs all aspects the driving task, to full automation where the system executes steering, acceleration, and deceleration of the vehicle while monitoring the driving environment and providing failsafe control measures if needed. (SAE, 2014). For more complete definitions of the levels and other terms please refer to the glossary.

SAE J3016 (2014) provides a descriptive technical taxonomy for the full range of automation in on-road motor vehicles including definitions for the advanced levels of automation, namely, the conditional, high, and full automation levels, where the dynamic driving task is performed entirely by an automated driving system while it is engaged for a specific driving mode (e.g., on the freeway) or for an entire trip on public roadways (SAE J3016). Automated driving at this level requires real-time control of steering, acceleration, and deceleration as well as robotic monitoring of the driving environment.

While the SAE taxonomy is similar to the BASt and NHTSA taxonomies it is not identical (SAE J3016). Please refer to the table in Figure 6 for a summary of the full SAE taxonomy including driver assistance and partial automation and the following descriptions for the higher levels of automation Level 3 through 5.

SAE Level	Name	Narrative Definition	Execution of Steering/ Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
	Human driver monitors the driving environment					
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
	Automated driving system ("system") monitors the driving environment					
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 6. SAE Definitions and Levels of Automation

For the purposes of this report an automated vehicle uses robotics to execute some or all of the driving tasks normally performed by the human driver. A fully automated, "autonomous," or "self-driving" vehicle, does all the essential things that an ideal human driver does to guide the vehicle to its destination. The vehicle knows where it is and where it is going; senses the road, other vehicles, pedestrians, and other objects in its environment; navigates and selects a path toward its destination; and then moves according to the path while avoiding objects by actuating steering, throttle, and braking. While a fully automated vehicle can assume and perform all the driving task of the human driver there are also lower levels of conditional or partial automation where vehicle control may be limited to specified conditions, e.g., highway traffic at low speeds, or isolated locations, e.g., campus shuttle. In conditional automation the human driver must take over control of the vehicle in situations outside the scope of the automated driving feature.

Examples of automated features include adaptive cruise control, lane keeping, collision avoidance, convoy and platooning, and all the way up to the fully automated self-driving vehicle, also known as an autonomous vehicle in the Department of Defense. In our Integrated Assessment, we find it useful to categorize developments in the automated vehicle community in accordance with SAE's defined levels of automation including partial automation (level 2), conditional automation (Level 3), high automation (Level 4), and full automation (Level 5).

As mentioned above the driver assist systems include features like antilock braking systems (ABS), electronic stability control (ESC), traction control system (TCS), crash imminent breaking (CIB), emergency braking assist (EBA), blind spot detection (BSD), lane departure warning (LDW), and forward collision warning (FCW). These function-specific systems are designed to assist the driver in controlling the vehicle and to improve overall safety. Other function specific driver assist systems include adaptive cruise control, lane keeping assist, and parking assist. However, these systems have already been introduced to the market and have widespread adoption and therefore are not a topic for this forecast. Likewise, more advanced combinations of these features like traffic jam assist and any simple coordination the adaptive cruise control and lane keeping features will not be addressed in this forecast.

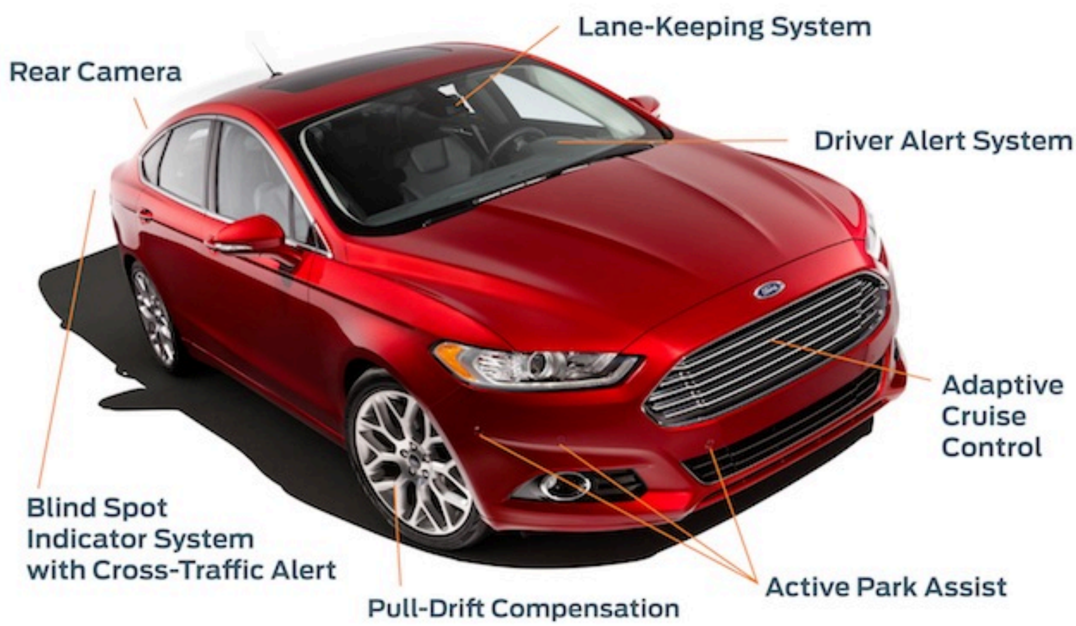


Figure 7. 2013 Ford Fusion, Introducing Automated Driver Assist Systems

Electric Vehicle Systems: Powering Sustainability

Automobiles need a source of energy to power their wheels. Sustainable transportation strategy needs to take into account the source of the energy, waste in the transition to powering the wheels, external impacts including greenhouse gas emissions, the ultimate cost of the fuel to the driver and society as a whole.

Historically in the United States the price of gasoline has been extremely low resulting in the rapid growth in demand for automobiles in the 20th century. Gasoline powered combustion engines produce both air pollution from carbon emissions are significant source of greenhouse gas. Furthermore, gasoline is a nonrenewable resource. There is a fixed amount of oil and as the stock is consumed the cost of delivering additional fuel increases. It's clear that at some point in our future will be in need to transition to alternative fuels. Sources like hydroelectricity, solar energy, wind energy, and biomass are not diminished by consumption and are likely to become less expensive events technology improves. Furthermore, petroleum sources are concentrated in geographic areas and distribution becomes an issue for nations that must import oil. The challenge for sustainable transportation in the United States is to become independent of oil imports and to decrease greenhouse gas emissions.

The cornerstone for sustainable transportation is reducing petroleum consumption and greenhouse gas emissions by increasing the efficiency of the internal combustion engine vehicle and increasing the use of biofuels, electricity, or hydrogen. Reducing the cost of these alternatives and increasing demand will require strong policies supporting research and development, subsidies, energy taxes, and/or regulation.

Perhaps the central issue facing all of the alternatives is the relative expense compared to today's vehicles including the high near-term costs for battery and fuel cell vehicles. While the driving cost per mile of vehicles powered by natural gas or electricity is lower than the conventional gasoline powered vehicle the vehicle cost is still significantly higher for these alternatives and this is likely to continue for at least a decade.

Increased vehicle efficiency is part of the roadmap with engine and drivetrain efficiency improvements. Reductions in weight and rolling resistance should improve the efficiency of all types of vehicles regardless of the fuel used. While natural gas vehicles have the great potential for reducing petroleum consumption they still have the issue of greenhouse gas emissions. The issues with batteries include limited range and longer recharge time despite the projected steep drops in the cost of batteries. However, given the overall fuel efficiency of electric motors, the decreasing cost of battery storage, and potential ubiquity of electric power as a last stage in the power conversion process, then electric vehicle appears to be a key component of the power delivery system in a course to sustainable transportation.

An electric vehicle uses an electric motor for propulsion and can be powered by one or a combination of three sources: (1) direct power from an external power station, (2) stored electricity originally from an external power source, and (3) an onboard electrical generator like a gasoline engine or hydrogen fuel cell. The common forms of electric vehicles are plug-in electric cars and hybrid electric cars. While electric vehicles and been around for over 100 years in the last few decades there's been a growing interest because of the environmental impacts of gasoline engines along with the concerns about peak oil and limits to growth.

Electric vehicles are different from fossil fueled vehicles because their energy is generated from a variety of sources including fossil fuels, nuclear power, hydroelectric, solar power, and wind power. Consequently the carbon footprint of electric vehicles depends a lot on the source fuel and the technology used for generating electricity. The electricity is generally stored on board the vehicle using a battery, flywheel, or supercapacitors. Another advantage of hybrid or plug-in electric vehicles is the use of regenerative braking to recover energy lost during breaking that can be captured and redirected to the battery.

Electric engines are very simple and efficient by comparison to combustion engines with net CO2 production about half that of a comparable combustion vehicle. The cost of charging electric vehicle is about 1/5 or even less the cost per mile for gasoline powered engines. The electric vehicles themselves do not produce local pollutants including noise pollution that is so common with internal combustion engines. Furthermore, even if the original source of energy is fossil fuel it is generally more efficient to control emissions at the coal or gas-fired plant. However electric vehicles have issues including limited range, longer refueling or recharge times, and higher initial costs.

There are a number of potential sources of electricity including onboard generators from diesel electric and gasoline electric using combustion engines in hybrid electric vehicles and onboard storage and using lithium ion batteries. There are also a variety of different types of powertrains including plug-in and hybrid electric vehicles. Battery electric vehicles run solely on electric motors and rechargeable batteries. Plug-in hybrid electric vehicles charge internal batteries via an electrical outlet, and has gas fueled engine when the battery runs out of charge. The extended range electric vehicles are similar to the plug-in hybrid but they do not use gasoline engines to provide mechanical energy to the drivetrain. Some electric vehicles travel around 60 miles on a single charge while some can go more than 200 miles. While a compact gasoline- only car costs around $1500 to fuel every year, and electric run car costs $421.

Electric vehicles typically charge from conventional power outlets or dedicated charging stations. As the demand for electric vehicles increases the demand for energy on the grid also increases along with associated emissions. Vehicles can be charged at home garages or at work if power stations are available. Curb stations have been designed to enable charging on city streets and inductive charging may provide added convenience while minimizing cabling and connection infrastructure. Long-distance travel can be facilitated with rapid charging along with possible designs for swapping of batteries or the entire vehicle chassis.

The automakers appear to be very committed to electric vehicles and major efforts are moving ahead at Tesla, General Motors, Ford, BMW, Nissan, Volkswagen, Mitsubishi and many others. While the number of automakers and models of electric vehicles is continuing to increase the challenge appears to be addressing the need for charging infrastructure. Drivers are accustomed to quick refills at the omnipresent gas stations and gasoline vehicles can easily travel hundreds of miles in a single trip. In order to manage range anxiety and for market penetration of electric vehicles to continue to grow this will not only require more chargers but the ability to charge quickly. One potential solution is to explore the potential for continuous inductive charging of vehicles traveling on designated lanes of the highway and controlled with self driving vehicle technology.

Conventional approaches to electric vehicle charging include (1) normal charging at home or in a public space using level I or level II voltage and 110 or 220 V for 6 to 10 hour charge, (2) 15 to 30 minute fast DC charging with a 24kWh battery pack requiring 96KW which is way over the power available in private homes, and (3) battery swapping at swapping stations which requires manpower and standardization. These approaches have their challenges including safety were electric shock may be caused due to rain, damage of charging plug in cable, and overall space requirements. Alternative approaches wireless power transfer using induction with strongly coupled magnetic resonance and high-efficiency inductive power distribution. The principles for inductive power transfer over distances of about a quarter wavelength for simple coupled models. Wireless power transfer includes electromagnetic induction, radiation, and electromagnetic resonance. Radiation approaches include radio waves, microwave, laser, and ultrasound. Qualcomm, Delphi, Plugless Power, KAIST, and others are developing variations electric vehicle wireless charging with the predicted market close to $17 billion by 2019. Challenges that need to be addressed in this area include magnetic field diminishing proportional to distance, the low values of mutual inductance, and the analytical difficulties of coil mutual inductance.

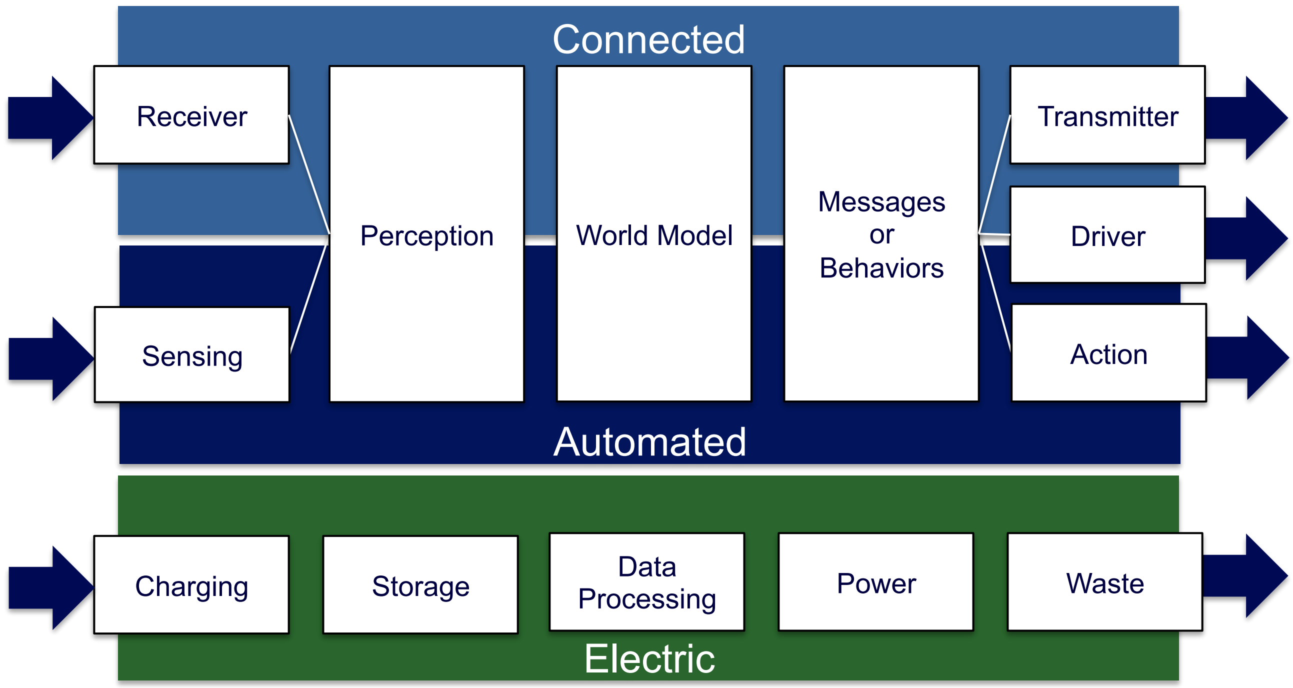


Figure 8. Automated Connected and Electric Vehicle Systems

Preliminary Conceptual Roadmap

In preparing for the expert survey unconnected automated vehicles we conducted a high-level analysis of the range of technologies to be addressed in the existing literature on the system impacts and potential contributions to sustainable transportation. The systems or technologies that we identified included telematics, driver assist, cooperative automation, vehicle-to-infrastructure communication, conditional automation, full automation, and cooperative driver assist. Other technologies or systems could have been included but this was our starting point in preparing our vision on the contribution of disruptive technologies to sustainable automotive transportation. In our review of the literature we identified a range of impact areas including safety, mobility, productivity, environmental, fiscal, and traveler convenience. These are likely to be contributing factors to the adoption of technologies from both the consumer and a public policy perspective. We then organized the specific impacts of each technology or system under it each of the impact areas. These cross impacts are listed in the table below with marketable impacts in the areas of productivity and convenience being represented in the green columns to highlight the potential for market mechanisms influencing their adoption. While there is also consumer interest in the remaining impact areas including safety, mobility, environmental, and fiscal, we also wanted to note the importance of public policy and promoting their adoption. After preparing the table and noting some of the specific impacts for each of the technologies in each of the impact areas we then went through a process of identifying potential priorities for each of the technologies. So, for example while vehicle telematics can provide positive impacts in the areas of safety through mayday services while also providing traffic information to avoid travel delays and entertainment while traveling we noted the core impact in support of sustainability as being the provision of navigation and route guidance to improve travel efficiency and in the future providing the capability of downloading three-dimensional maps for localization and higher levels of automation. Similarly, as we went down the list of technologies we noted that the driver assist features in the new vehicles coming to market potentially assist with reduction in crashes while also increasing the convenience of driving. Cooperative automation supporting vehicle to vehicle communication supports a marketable service of cooperative adaptive cruise control and truck platooning as well as passenger vehicle platooning or convoys. This is a marketable service is likely be provided through a market to fleet operators that has a related impact of reducing environmental emissions.

Technologies	Safe	Mobile	Productive	Clean	Fiscal	Convenience
Telematics, 4G, LTE	**Smart Devices Distract** Mayday	Navigation, Route Guidance, **Map Download**	Traffic Information Avoiding Delay			Entertainment, Texting Smart Devices
Driver Assist moving to "Crashless" (radar/vision)	"**Crashless**" ABS, ESC, TCS, CIB, EBA, BSD, LDW, FCW Collision Avoidance					ABS, ESC, TCS, CIB, EBA, BSD, LDW, FCW, Collision Avoid. Self Parking
Cooperative (V2V) Automation	CACC Cooperative Collision Avoidance (CCA)	CACC Truck Platooning Car Platooning	CACC **Truck Platooning** Car Platooning	CACC Truck Platooning Car Platooning		CACC Truck Platooning
Vehicle-to-Infrastructure (V2I)		Congestion Pricing, Intersection Coordination		Congestion Pricing, Intersection Coordination	**Automated Road Pricing and Tolls**	Intersection Coordination, Automated Fees
Conditional or Limited Automation		Last Mile Campus Shuttle	**Highway Commute (HC)**	Last Mile **HC Increases Demand**		Traffic Jam Assist, LK & ACC,
Fully Automated or "Self-Driving" Vehicle		**Self-Driving(SD)/Autonomous Taxi**				Self-Driving Car Autonomous Taxi
Cooperative Driver Assist (V2V) supporting "Crashless"	V2V Warnings e.g., blind intersections, Passing oncoming					V2V Warnings

Figure 9. Cross Impact Matrix Supporting Vision and Questionnaire Development

Vehicle to infrastructure communication systems will not only potentially provide private information like the telematics services but it can also provide public information to both riders and drivers of vehicles in support of more efficient multimodal transfers. However, the greatest potential for vehicle to infrastructure communication is more likely in the area of supporting electronic payment systems for automated road pricing including congestion pricing and extending tolls to surface streets. In the longer term vehicle to infrastructure communication can assist automated vehicles with coordination of traffic maneuvers at intersections and coordinating vehicle maneuvers in a broad range of potential traffic management scenarios including speed control and merging.

The automated vehicle, ranging from conditional automation but is limited to specific circumstances like traffic jam assists along the freeway or simply automated commuting along the freeway to full automation where self driving vehicles can potentially operators taxis are chauffeurs, provide services and conveniences are likely to come to market further out on the timeline. However, systems like automated freeway commuting are likely to be marketable products with significant consumer demand at the right price and provide benefits like productivity by enabling the driver to multitask and freeing the driver to attend to other matters and entertainment supported through consumer electronics. Theoretically be his will also improve the safety of the vehicle by reducing driver error. Another form of high automation is the campus shuttle that will transport passengers at low speeds in areas where there is limited access. These shuttle vehicles will need to maneuver at low speeds and avoid pedestrians and can potentially provide first or last mile transportation options to the mobility disadvantaged. At the far end of the planning horizon is the self driving vehicle were autonomous taxi but has the potential for improving mobility for all including the elderly, the disabled, and anyone without a drivers license. The self-driving vehicle, again, has the potential for making dramatic improvements in mobility, productivity, and convenience. Vehicles with cooperative driver assist through vehicle-to-vehicle communication have the potential to reduce crashes through early warning systems, for example, at blind intersections, when passing with oncoming traffic, and when the driver is distracted.

In the process of preparing this cross impact matrix we also identified several negative impacts that could influence the path to sustainable mobility. For example, the potential for driver distraction from cell phones and other smart devices in the telematics area is a motivational force in the search of a solution to driver distraction and driver error that results in crashes, property damage, injury, and fatality. This is a serious problem that has been brought to national attention by the US Department of Transportation and the media and those affected by the consequences. This is also a potential force for increasing the demand for safer vehicles that have active safety technologies and driver assist functionality. As the sensing and control technology evolves and becomes more cost-effective the cars of the future are more likely to help the driver avoid and/or manage potential crash situations and could support a trend toward zero crashes or zero injuries or fatalities.

Another potential negative impact called out in the table is the potential for the more highly automated systems to reduce driver stress and increase their available time and thereby increase the demand for road travel with more trips or longer distance trips and thus increasing vehicle miles traveled and contributing to increased congestion. There is also some speculation that by decreasing the negative valence associated with travel back people will be willing to make longer trips and this could contribute to the continued trend in suburbanization and the associated freeway traffic jams. Both the issues of increasing travel demand and the distracted driver were addressed in our survey.

The purpose for going through this exercise of prioritizing potential impacts from each of these technology areas was to assist in the formulation of our idealized vision and to help with our formulation of questions for the expert panel. This was a preliminary step in preparing for the expert panel survey.

Now I want to turn to the preliminary roadmap for sustainable automotive transportation that we presented to both the members of the expert panel and the organizations and transportation agencies with which we conducted outreach. The figure below attempts to capture this the high level roadmap for automotive transportation with the support of multimodal transfers. While today we are engulfed in the legacy of freeway construction, suburbanization, and gasoline-fueled internal combustion automotive transportation, we are already making headway in the design of safer and more fuel-efficient vehicles to address some of the problems in our transportation system. However, with increasing population, increasing greenhouse gas emissions, international competition for fuels, and are continuing effort to maintain our economically competitive status we need a transportation system that will deliver ever increasing mobility at lower economic and social cost. The vision we posed for our expert panel is that in the long-term future of the automobile will be connected, automated, and electric supporting universal mobility, efficient travel, economic competitiveness and traveler safety. The vehicles of tomorrow will be fuel-efficient and highly automated offering the traveler more time in their day and reducing emissions to a sustainable level. This will be supported by communication system that will enable marginal cost road pricing to help manage congestion and travel demand. It will also be enabled by a geographically dispersed electric vehicle-charging infrastructure that could potentially feature inductive charging at specific locations including designated lanes along the freeway. The questions we posed for a panel of experts addressed what needs to be accomplished to enable this vision, what the steps are to make this happen, and when activities will need to occur.

The figure below summarizes the roadmap that emerged from our expert panel and the survey process with the green boxes addressing energy, blue boxes addressing automation, and the brown boxes addressing connectivity. This figure was framed by the survey responses and answers the question of how we will accomplish this vision.

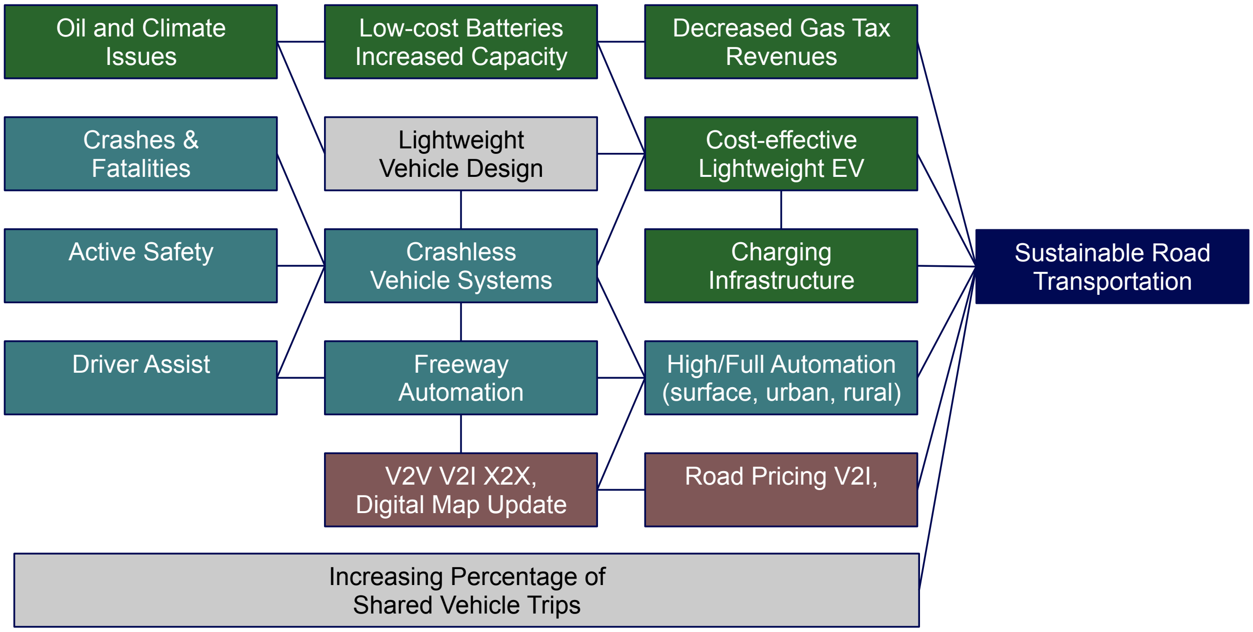


Figure 10. Summary of the Vision and Topics for Expert Survey

The next three sections will provide overviews and summaries of panelist input specific to automated vehicles, connected vehicles, and electric vehicles. While the topic of telematics was not an area of concentration for the survey it was addressed in a couple of the questions related to connected vehicles addressing the subjects of digital map downloads and alternatives to DSRC. Furthermore, the topic of Telematics is relatively mature in comparison to the other topics of focus in this report. Therefore, we have combined the discussion of both short-range and long-range communications with the vehicle in a single section on connected vehicles. Note that telematics and specifically 4G LTE communication is an essential component in the roadmap for supporting both digital map updates and road pricing. However, this topic will be addressed in the section on connected vehicles.

Automated Vehicles

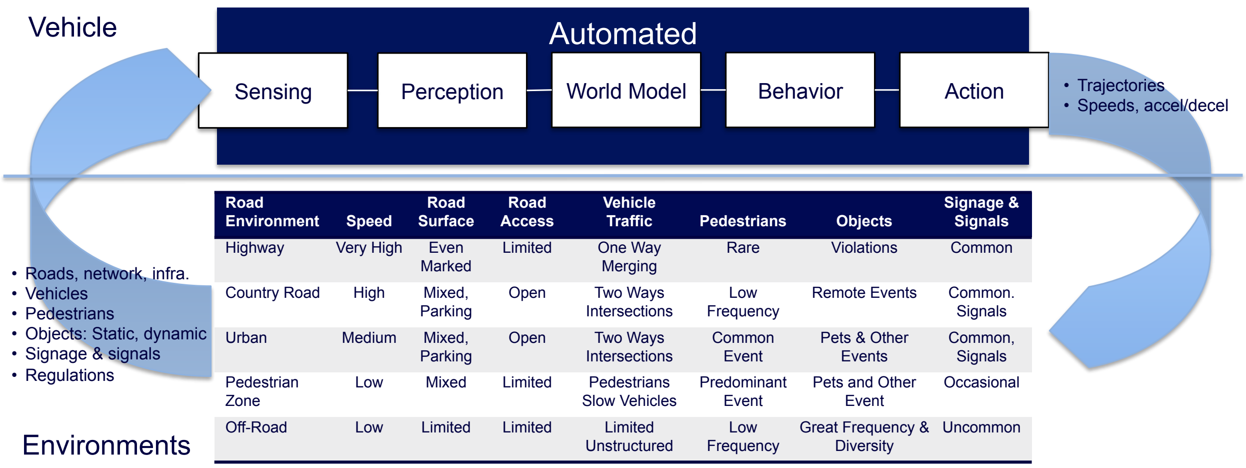
As the computational power of automotive electronics continues to grow along with the shrinking of associated hardware the vehicle will continue to acquire higher levels of intelligence and perform some of the driving functions automatically. Today, only 50 years after the early introduction of automation into the automobile, the design of the automobile is being transformed fundamentally. At the level of vehicle design, automation requires the ability to achieve unsupervised interaction between various sensors and actuators, along with the ability to communicate among various subsystems. This is all driven by advances in miniaturization, cost, and performance of electronic components and the standardization of cross system functions such as networking and communication.

Many of these functions require embedded computer system with a dedicated function within a larger mechanical or electrical vehicular system or functional subsystem, often with real-time computing constraints. With higher degrees of standardization and modularization of embedded systems the implementation of vehicle automation is advancing and will continue at an increasing rate. For vehicle design the research will focus on reference designs and architectures, seamless connectivity and middleware, and system design methods and tools. The collective target is a generic platform of vehicle components for self-driving vehicles. This platform will help promote standardized interfaces for each component and support the extension and growth of component and automated vehicle system functionality. From the perspective of sustainable transportation the goal is to reduce cost and promote the lowest possible power consumption. Additional goals include the ability to self configure and self organize the components of the automated vehicle system. This may involve ubiquitous connectivity schemes and networks for the subsystems.

Finally, the research community need to address design methods and tools for the automated vehicle including open interface standards, automatic validation and verification, testing on track and on road, and the use of simulation for testing and evaluation. Methods and tools will be coupled with progress in the rapid design and prototyping of automated vehicle systems.

Figure 11. Fords Automated Test Vehicle

The emerging approach to vehicle automation 's vehicle centric and that the goal is to automate the vehicle navigation functions under computer control and thereby taking the driver out of the control loop. All the sensory, perception, processing, and control functions that have historically been the domain of the driver become the responsibility of the onboard information and control computer system. The onboard computer senses and understands the vehicle situation within the context of the environment and decides the most appropriate maneuver to move the vehicle toward its destination. The system architecture includes what were historically cognitive functions of perception, understanding, and movement. A core function of automated vehicle movement is the perception and recognition of obstacles along the desired path. The robotics industry has focused on the development of portfolio alternative sensors to address the needs of perception and navigation and include ultrasonic sensors, infrared sensors, video cameras, and stereo vision, as well as radar and scanning lasers. The overall architecture requires for interdependent systems including a perception system comprised of sensors to capture the scene and recognize potential features of interest, the navigation system that uses algorithms for understanding the situation in generating a path for the vehicle to follow a control system that receives commands from the navigation system in terms of heading and speed and ensures that the vehicle follows the desired trajectory, and a supervisory control system that maintains the coherence of these interdependent systems and insurers of the vehicle navigate safely or in the case of failure, the vehicle fails safely. These functions depend on the status of the vehicle and its position, speed, acceleration, your rate, and other elements of the vehicle state that enables estimation of the vehicle dynamics and the position of the vehicle with respect to a global reference frame in the world model.

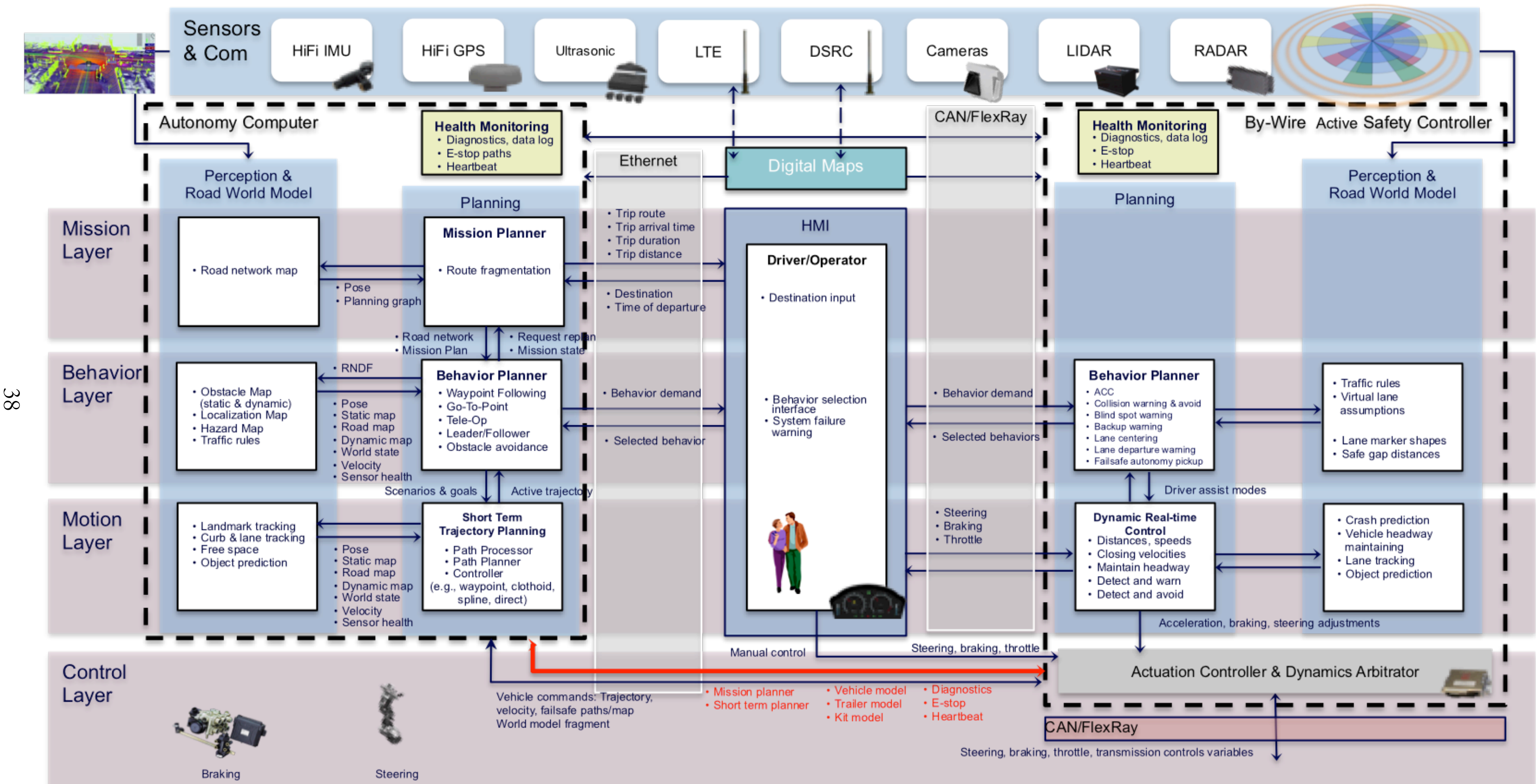


Road Environment	Speed	Road Surface	Road Access	Vehicle Traffic	Pedestrians	Objects	Signage & Signals
Highway	Very High	Even Marked	Limited	One Way Merging	Rare	Violations	Common
Country Road	High	Mixed, Parking	Open	Two Ways Intersections	Low Frequency	Remote Events	Common. Signals
Urban	Medium	Mixed, Parking	Open	Two Ways Intersections	Common Event	Pets & Other Events	Common, Signals
Pedestrian Zone	Low	Mixed	Limited	Pedestrians Slow Vehicles	Predominant Event	Pets and Other Event	Occasional
Off-Road	Low	Limited	Limited	Limited Unstructured	Low Frequency	Great Frequency & Diversity	Uncommon

Figure 12. Vehicle and Environment in Closed Loop Automated Vehicle System

The degree of difficulty of sensing and maneuvering through the environment depends on the vehicle capabilities and the road environment including dynamic objects like vehicles and pedestrians. The diagram depicts a range of road environments that the automated driving system must recognize, understand, and manage through effective actions. While the control of these actions is relatively simple to control through steering and speed trajectories the specific maneuvers to the contrary can be very complex and difficult demand depending on the environment. So, for example, the high-speed highway environment with limited access and traffic moving in a single direction may have a different degree of difficulty than a low-speed pedestrian zone were no automobiles are allowed but there is dense pedestrian traffic. The challenge of replacing the driver with an automated system depends a lot on the road environment.

The automated system also engages in behavior planning where it computes a sequence of actions that change the world from the current state to a desired state. Planning requires representing actions along with objectives or resource optimization criteria, and algorithms for computing the action sequences in a manner that conforms to the constraints of the problem. While geometric path planning fairly is well understood, that is, the on-the-fly optimal path is a route that optimizes feasible traversability and minimizes travel time, it is more difficult to plan and execute maneuvers that include multiple core operating vehicles in the complicated road network environment.


Sensors & Com
HiFi IMU
HiFi GPS
Ultrasonic
LTE
DSRC
Cameras
LIDAR
RADAR
Autonomy Computer
Health Monitoring
• Diagnostics, data log
• E-stop paths
• Heartbeat
Ethernet
Digital Maps
CAN/FlexRay
Health Monitoring
• Diagnostics, data log
• E-stop
• Heartbeat
By-Wire Active Safety Controller
Perception & Road World Model
Planning
Planning
Perception & Road World Model
Mission Layer
Behavior Layer
Motion Layer
Control Layer
• Road network map
Mission Planner
• Route fragmentation
• Pose
• Planning graph
• Road network
• Mission Plan
• Request replan
• Mission state
• Trip route
• Trip arrival time
• Trip duration
• Trip distance
• Destination
• Time of departure
HMI
Driver/Operator
• Destination input
• Behavior selection interface
• System failure warning
• RNDF
• Obstacle Map (static & dynamic)
• Localization Map
• Hazard Map
• Traffic rules
• Pose
• Static map
• Road map
• Dynamic map
• World state
• Velocity
• Sensor health
Behavior Planner
• Waypoint Following
• Go-To-Point
• Tele-Op
• Leader/Follower
• Obstacle avoidance
• Behavior demand
• Selected behavior
• Behavior demand
• Selected behaviors
Behavior Planner
• ACC
• Collision warning & avoid
• Blind spot warning
• Backup warning
• Lane centering
• Lane departure warning
• Failsafe autonomy pickup
• Traffic rules
• Virtual lane assumptions
• Lane marker shapes
• Safe gap distances
Scenarios & goals
Active trajectory
Driver assist modes
• Landmark tracking
• Curb & lane tracking
• Free space
• Object prediction
• Pose
• Static map
• Road map
• Dynamic map
• World state
• Velocity
• Sensor health
Short Term Trajectory Planning
• Path Processor
• Path Planner
• Controller
(e.g., waypoint, clothoid, spline, direct)
• Steering
• Braking
• Throttle
Dynamic Real-time Control
• Distances, speeds
• Closing velocities
• Maintain headway
• Detect and warn
• Detect and avoid
• Crash prediction
• Vehicle headway maintaining
• Lane tracking
• Object prediction
Acceleration, braking, steering adjustments
Manual control
Steering, braking, throttle
Actuation Controller & Dynamics Arbitrator
Vehicle commands: Trajectory, velocity, failsafe paths/map
World model fragment
• Mission planner
• Short term planner
• Vehicle model
• Trailer model
• Kit model
• Diagnostics
• E-stop
• Heartbeat
CAN/FlexRay
Steering, braking, throttle, transmission controls variables
Braking
Steering

Sensing and Perception

Sensing and perception enables the automated vehicle system to navigate through environments and manipulate obstacles by transforming signals from the sensors into knowledge about situations and events in the real world. Perception uses sensors, that is, the hardware, and also uses sensing software to transform raw input like lights and camera images, into information that can be used to control the vehicle.

While it is fairly straightforward to measure distances and sizes in the vehicle environment, for example lidar and radar can produce the range of an obstacle like a vehicle, it is more of a challenge to recognize and classify the data. It is also difficult to tell whether an object is a soft bush or hard rock, street sign or a pedestrian. Where is a human is likely to know that ball bouncing across the road suggest a child may run into the road, the computer will have a more difficult time drawing this conclusion.

Perhaps the primary reason for improving navigational perception is to help drivers to drive more safely. Drivers often cannot react fast enough to navigate effectively and complicated environments. However, the more fully automated vehicles are designed to navigate and to drive themselves. Navigational perception can also reduce the cognitive workload of the vehicle operator. That is, when the vehicle navigates then the operator can attend to other things. Perception can also be extended to vehicle health for detecting faults and supporting graceful degradation of performance and recovery from these faults.

Some of the issues that need to be addressed in the area of Sensing and Perception for active safety, driver assist, and higher levels of automated vehicle systems include:

- Develop improved onboard computer vision algorithms to recognize and classify both static and dynamic objects within the sensor device in order to reduce the data avalanche that can potentially overwhelm the network bandwidth.
- Improve the graphics processors for vision algorithms to overcome inefficiencies in general-purpose chips.
- Develop high-speed obstacle detection algorithms for complex urban environments with numerous dynamic obstacles, like pedestrians and bicyclists, extensive signage, and complicated traffic signalization.
- Because all sensors have limitations, for example, radar and camera sensors that are susceptible to changes in lighting in the presence of dust, smog or fog, another high priority is the integration of multiple sensors for improved perception with an eye toward future upgrades and extended capability.
- Focus more on the development of advanced algorithms for existing sensors rather than investing in the development of new sensors. This includes extracting more information from existing data and using this information and more innovative ways.
- Health maintenance systems are designed to detect faults and recover from general hardware and software failures as well as detecting and recovering from loss of network connectivity. A serious concern for vehicle-to-vehicle communication systems is the loss of wireless network connectivity in the context of an event.

Machine Learning

Machine learning systems can mine large amounts of real-world data to find reliable patterns to help in the development of automated vehicle systems. For example, there are a large number of well-developed learning techniques that were successfully demonstrated in the DARPA challenges that helped in the development of computer vision, natural language processing, and planning systems for the vehicles. Learning systems are especially promising in helping the vehicles to handle more complex urban environments where there are numerous environmental cues and cooperative vehicle-to-vehicle behaviors required. One example approach is cross-modal sensory training where, for example, short range LIDAR data on a terrain can be used to train longer-range vision systems.

One of the challenges is machine learning generally requires extensive training date that is often expensive to acquire. Using techniques for reducing the amount of supervision that learning requires will help in this area. While reinforcement learning can help to minimize supervision for training this approach often required a larger number of multi-step training experiences. Imitation learning is another promising approach where the automated system observes a human perform the navigation task and learns through the observation experience. Additional research on a number of related approaches including reinforcement learning, transfer learning, interactive reward shaping, advice taking, and other approaches should be a priority. Furthermore, since one of the primary objectives of self-driving vehicle is to detect and recognize unusual but critical objects in the field of view, for example, a ball or balloon that could suggest a child is following behind, more research needs to be devoted to identifying and achieving high detection rates for anomalous "outlier" objects without also generating unacceptable numbers of false-positive detections.

User Interface

The human machine interface (HMI) for automated vehicles is concerned with the bidirectional cognitive interactions between the vehicle and the vehicle operator. Automated vehicles are distinctly different from computers in that they have interactions with the physical world with some degree of autonomy. In order to better understand the HMI for automated vehicles it is necessary to address number of questions, for example:

- How do the operator and the automated vehicle communicate?
- How shall we model the relationship between the driver and the automated vehicle?
- How can we study and enhance the teamwork between the operator and the automated vehicle?

It can benefit the designer to focus on the HMI versus the platform because this helps to improve performance, reduce the cost of operating in designing the platforms, and increases the adaptability and acceptance of new vehicle systems more quickly. Furthermore, a human centered design approach helps with producing effective interfaces with better with better performance, reduced errors, and greater trust and user acceptance.

Methods of communicating with automated vehicles need to improve and can with the possible adoption of natural language and higher resolution display technology. A natural user interface will enable effective interaction with the human operator in the vehicle. A good interface supports rapid training of novice drivers as well as effective transitioning to higher levels of expertise. Furthermore, the operator should be able to see what the vehicle is doing while an automated modes. It also helps if the interface is adept at learning, understanding, and accurately activating human commands. Natural language is the most normal and intuitive way for the operator to instruct the automated vehicle. Research is needed to develop a user interface that can effectively communicate using human language. While there have been major advances in language-based interfaces for smart devices additional research is required to make this type of interface useful for commanding automated vehicles including work in language interpretation, and execution of instructions, and linguistic expressions of spatial relationships.

Driver Complacency

> **Round 1; Question 3**: As vehicle automation expands in the United States, what features will OEM's include in their vehicles to help overcome driver complacency issues caused by their reliance on automation?

In general, majority of panelists expressed that this is a critical challenge that remains an open topic for further investigation and exploration. The followings summarize the experts' opinions gathered through the survey:

- One single mode of human-computer interaction will probably not be sufficient since it is easy to become "immune" to the single mode with exposure and learn to ignore it. Thus, it may be required to switch between different modes of interaction in a somewhat random manner. Technologies within the car such as sound alerts and vibration of steering-wheel and seats may be used. Specially designed UIs that alert the driver from time to time may also be used. Technologies for monitoring driver attention will also be developed. Additionally, a user's phone or computer or e-book reader may be hooked up to the car's "brain" and the user may be alerted through the device she/he is currently using.
- While the above options/solutions are deemed to be necessary, the topic of complacency depends very strongly on which level of automation is being considered. For a Level 1 system the automakers already offer level 1, and generally do not include specific additional features to address this, other than not combining too many level 1 features (turning it into level 2). For Level 2 systems the automakers will likely need to include features (e.g. driver in seat detection, eye gaze detection, hands on wheel detection). Many of these features can already be found in production models. Regarding a Level 3 system, the automaker needs to ensure that the driver can re-take control in the amount of time designed into the system. So depending on what time is chosen (lead time required for driver to take over the vehicle control), this may include detection of the driver in the driver seat, detection of hands on wheel, etc. Finally, a Level 4 system in principle does not require any features to overcome driver complacency.

While the above summary was a repeated theme across all the responses received, two of the panelist believed that complacency will not be a problem because the technology will improve faster than complacency taking hold in the driving public. People will still like to drive at least some of the time for a very long time. Plus since the automation will drive better than us, complacency is a good thing and the vehicle will warn the driver in plenty of time that things are about to get dicey.

An interesting analogy put forward here points out that OEMs did not actively try to teach drivers how to drive manual transmissions, after the automatics were introduced. Arguably the majority of the US drivers do not know how to drive a manual transmission vehicle. The required driving skills of the future will be far more limited than today and that's OK.

Driver Monitoring (NHTSA Level 2)

In this section panelists provided their comments regarding the questions if driver monitoring will be required for Combined Function Automation (Level 2) vehicles to ensure the driver's capability of taking control of the vehicle when necessary? And, what kind of driver monitoring will be necessary? Majority of respondents, except for four, agreed that driver monitoring should be required for Level 2 automation since the definition of level 2 required the driver to be in the control loop. As a result, it becomes necessary to monitor the driver and ensure his or her engagement with the task in hand. Followings summarize some of the most important comments and feedback received from the panelists:

1) Additional research is required to best understand the options and how to meet customer expectations. Having the feature, but becoming annoyed by how it operates is a significant risk to deployment.

2) A level 2 system has the risk of appearing like a level 4 system to a driver, but not having the high level of safety. Hence, it becomes imperative to monitor the driver, ensuring of his ability to take over the vehicle's control in case a situation arises.
3) There must be driver monitoring for obvious manifestations of distraction and also performance monitoring (e.g., car following behavior). These are necessary because the real world traffic environment and effects such as weather, plus unpredictable events, will require vigilance. Vigilance is nearly impossible with low work load, so monitoring will require subsequent action or activity to be given to the driver as well.

Modular Design

Round 1; Question 6: How will modular design and customization play into vehicle automation?

Like the other topics investigated in this survey, there seems to be consensus amongst the panelists regarding modularity and vehicle automation, except for six panelists who expressed no opinion due to their lack of familiarity with the topic. The response gathered from the panelists can be broken into the following thematic areas:

- Modular Design from Customer Perspective: Modular design will be critical to sales and consumer acceptance mainly for two reasons. First, with a modular software design, it will be possible to sell different bundles of features to different users at different price-points so that a user can choose a "feature update" by paying for just the feature desired. This will make different automated functions available (given hardware availability) to different users based on their price-range, leading to wider market acceptance. If users can customize the car to their preferences, they are more likely to buy such a car. For example, people have different driving styles, and a person with a cautious driving style will probably not feel comfortable in a car that drives in a sporty manner. Second, Customization increases a user's trust in the vehicle that is driven by age and other demographic factors. For example, if the cautious users can customize the car to drive like themselves, they are likely to have more trust in the car. Or, for younger users customization is a matter of showing off their individual style and they would prefer cars with such features.
- Modular Design from Manufacturer Perspective: First, modular software if shared between different developer and OEM's will lead to a much faster development process resulting in more functions since people will not have t keep reinventing the wheel. Software is about 3 times quicker in modifications than mechanical product development. Software will be required to be open and consistently updateable as the vehicle slowly mature and costs of manufacturing are winnowed out. Second, Modular design and construction becomes much more feasible if the vehicle does not have to be designed to meet safety requirements. Assuming this goal is reached and the fleet is 100% zero-crash vehicles (or if vehicles do not have to co-exist with traditional automobiles and heavy-duty trucks) then the opportunity to design vehicles differently or modularly to exploit low cost materials or locally available resources is significantly enhanced.

The topic of modular design is expected to be initially driven by concerns and interests related to interoperability and reduction of production cost of automation equipment. Hence, modularity needs to be implemented at both hardware level (MCUs, sensors, interfaces, etc) and software level (OS platforms, middleware, application software, etc). As a result, industry is expected to move more aggressively towards standardization.

Driver Monitoring (NHTSA Level 3)

Similar to the question regarding Level 2, panelists were asked if driver monitoring will be required for Level 3 automation. This stage of automation is deemed as a transitional stage by most of the industry that as a result, introduces interesting complexities into the mix. Nevertheless, analyzing the comments collected, many of the respondents indicated that monitoring of the driver will still be required though they did not seem to agree to what degree.

- Driver monitoring will not be necessary. When such a vehicle wants the driver's attention, it will alert the driver by various means. If the driver fails to do what is requested, the vehicle will be equipped with a "safe-stop" functionality to bring the vehicle to a safe stop.
- Driver monitoring and related to wellness/health monitoring will be required especially as population ages and older people have autonomous driving-enabled personal mobility. Monitoring for health issues that may limit ability of driver to re-engage will be important in determining if vehicle needs to bring vehicle to controlled stop and contact EMS.
- This depends on the requirement for takeover time planned in the system design. If the time is quite long, then the only monitoring required might be to make sure the driver is in the driver seat. If it is shorter, additional monitoring of hand position, eye gaze, or foot position could be required

Round 2; Question 5: Which of the following forms of localization will be sufficient to enable safe and reliable on-demand entrance-to-exit highway automation?

- A combination of precise LIDAR and map-based localization
- A combination of GPS-based localization along with sensors (e.g., vision and radar)
- Another form of localization (please explain below)
- If you selected "Another form of localization," please explain that form of localization here:

Table 2. Localization Approaches

Localization	Percent Agree
LIDAR and digital map-based	30%
GPS & sensors	40%
Other	30%

Some comments to the responses included:

- Lidar & high precision maps or GPS & other signals, high precision maps and camera & radar Price will determine which wins--both are possible Lidar needs to be smaller to not stick out for design reasons
- GPS is enough. Localization is not a problem. We drive with no localization help other than vision. Why should these systems have anything more? End of story.
- A combination of GPS-based localization along with sensors (e.g., vision, radar, lidar) and map-based localization
- GPS, sensors (lidar and vision), and maps (with localization artifacts but not full 3D).
- Pre-built maps will be required. A combination of GPS + map-based localization will be required. Map-based localization can be done using various kinds of sensors such as LIDAR, visions, radars etc. In general, localization without GPS requires feature rich environments. In environments with less features, aliasing can occur in sensor data and GPS will be necessary to resolve this aliasing.
- Combination of GPS, DSRC, Vision/Radar or LIDAR and map-based localization, perhaps with Wi-Fi ranging will provide most robust method of localization needed for safety and reliability

- Vision + Inertial with reduced reliance on GPS
- There are many new technologies currently being developed with LIDAR, RADAR, Flash LIDAR, and VISION. The answers to this question will be completely different in 5 years.

Event Data Recorder

Panelists were asked about their opinion if deployment of a comprehensive Event Data Recorder (EDR) to capture data from automated vehicles can play a critical role as an enabler. All of the panelists unanimously demonstrated a consensus that EDRs will be required for all levels of vehicle automation (level 2 through 4), except for one who believed EDRs will be capturing only accident data as opposed to capturing comprehensive data. The expert panelists expressed the following reasons to be the main drivers of deploying and utilizing EDRs:

- Accident re-construction to assist with liability and litigation issues caused by possible accidents involving automated vehicles.
- General purpose data mining and long term trend analysis that could assist with unearthing travel patterns and other beneficial information.
- Monitor system performance and prevent failures from occurring (diagnostics for monitoring any degradation and recalling vehicle or disabling vehicle until fault is fixed).
- Improve system performance by tuning algorithms that requires a learning or AI machine. This means that such data must be collected as part of the suite.

Weight and Size

The question was asked from the panelists to elaborate on "What impact will vehicle automation have on future vehicle's size and weight? Which level of automation will have the most conspicuous impact on future vehicle's weight and size?"

Round 1; Question 2: What impact will vehicle automation have on future vehicle's size and weight? Which level of automation will have the most conspicuous impact on future vehicle's weight and size?"

The results gathered from the opinions of experts reveal that there are a few factors that affect the weight and size of future vehicles. The overall analysis of the comments received shows that:

- In near term, there is a very little impact in terms of size and weight as passenger vehicles need to provide the highest level of protection for the passenger and reducing the vehicles' size and weight is not aligned with this objective even with market introduction of Level 3 automation since there are still legacy vehicles on the road. However, if there is any impact, it is more along the line of adding weight as the technology requires additional sensors and equipment. However, this weight addition is not considerable.
- In long term, however, by introduction of Level 4 automation there is the opportunity of reducing vehicles' weight and size since these vehicles are more advanced and much closer to the vision of "crash-less". Nevertheless, in early years of deployment, there are still legacy vehicles on the road that increase the chances of accidents. As a result, smaller lighter vehicles may appear in confined or separated environments first. Needless to say, reducing the weight and size of the vehicle and adopting new styles and design principles requires changes in the regulation that could acknowledge the safety benefits and impacts of Level 4 automation, allowing a paradigm shift from how vehicles are designed.

Physical Infrastructure

Nowadays, many in the industry are concerned and curious about the impact of vehicle automation of existing infrastructure (bridges, highways, tolls, etc) and vice versa. Responses provided by the experts are quite revealing and are summarized below:

- While many talk about creating dedicated lanes and other infrastructure changes, panelists in this survey have unanimously mentioned that there will be no major infrastructure change required to enable the operation of automated vehicles (i.e. Level 3 and 4). This is believed to be one of the greatest benefits of vehicle automation by increasing the efficiency of the existing infrastructure. Also, depending on infrastructure changes will limit the market potentials of the technology as it can be only used in certain environment and large scale ubiquitous deployment may eventually falls out of favor due to high infrastructure costs.
- Though the physical infrastructure may not witness any major change, it is becoming increasingly important to implement standardized traffic signs (e.g. traffic lights, stop signs, work zones, etc) and maintenance procedures (e.g. lane markings) across state lines. Currently difference states have different guidelines related to design and positioning of traffic signs. This also applies to lane markings as some states use more reflective and better maintained road markings compared to other states.
- In addition to the minimal or no change to the infrastructure, the need for a unified approach towards traffic signs and road maintenance, there is also a need to move more aggressively towards digital infrastructure. This can range from providing high fidelity digital map of the road network, improved GNSS/GPS, or more pervasive deployment of V2I infrastructure.

Vehicle and Capability Prototyping

Operational prototyping is a flexible and robust tool we intend to use to a greater extent in evaluating new systems and technologies, stimulating design teams and exploring the realm of the possible without needing an early commitment to procurement. Capability prototyping allows us to develop and demonstrate concepts and technologies at varying degrees of maturity as a hedge against the technical uncertainty of an unanticipated threat, to enhance the interoperability or extend the utility of existing systems and to enable the introduction of more capability and affordability. It is our intent to employ capability prototyping more for subsystems and force multipliers, but we expect to do some platform prototyping as well.

Test, Evaluation, Validation, and Verification

Automated vehicle systems present many unique challenges for testing performance, safety, and reliability. A comprehensive evaluation will address system performance and reliability including safety, driver/operator expectations and mental models for interacting with the vehicle, failsafe and fail operational properties to ensure recovery, Cybersecurity for protecting vehicle and data, and interaction with other vehicles and infrastructure. Whereas driver assist functions of a vehicle can be developed under specific potential crash scenarios the more fully automated self-driving vehicle requires testing for reliable performance in repeatedly performing standard maneuvers in a full range of everyday and exceptional dynamic environments and situations. A complete evaluation will address a systems safety, performance, and the interaction of humans with the automated system. The evaluation protocol should be able to predict the systems behavior and decision processes. It must also be able to characterize the environment for the vehicle and assess the accuracy of the environmental sensing and the world model based on the sensing. Furthermore, the testing and evaluation approach needs to evolve from repeated testing is well-defined scenarios to more dynamic testing of automated system decisions in less structured naturalistic on-road environments. Testing and evaluation approaches can range from simple surveys and human factors experiments to bench-top engineering experiments with hardware in the loop (HIL) to the testing of specific maneuvers on test tracks to on-road testing in less-structured road, traffic, and weather environments. The testing of vehicle dynamics in simulated traffic environments will be necessary to address myriad of road network and traffic scenarios that an automated vehicle may encounter. This requires a more comprehensive systems engineering approach like that for functional safety in ISO 26262 and a reference framework for analyzing the system. Any testing and evaluation process will address the following questions:

- Does the automated vehicle system function correctly in specific operational scenarios, across the entire range of design conditions?
- Does the automated vehicle handle specific unusual and safety-critical events appropriately?
- Does the automated vehicle know when it is about to lose the ability to provide safe operation?
- Will the automated vehicle reliably and gracefully transition into fail-operational or fail-safe mode when an onboard failure occurs?

The testing and evaluation approaches must convince the designer, user, or certification authority that the system s as it was developed is safe to use and will fulfill its intended function and the real-world environment. Both off-road and on-road testing requires instrumented vehicles that have measuring systems to perform complete dynamics tests. Validation deals with the consistency between the information model of the user's intention and the behavior of the systems-under test specification. Verification deals with the consistency between a given (formal) specification and the system-under-test specification. It can be a challenge to test dynamic real-time automated vehicle can be a challenge because a probe effect modifies the temporal behavior of the system and it is often difficult to isolate loci of control in distributed systems. New approaches are needed to assist with testing the components of a distributed system and for injecting faults for reliability forecasting.

Objective benchmarking of perception and navigation including localization and mapping can only be achieved by comparing experimental results against reference data. The practical problem is the generation of the ground truth data. In doing experiments with ground truth reference researchers aim to measure the objective performance of the vehicle system or component of the system including algorithms. Based on this benchmark it is possible to demonstrate the effectiveness of the systems or component. An important research priority is the development of ground truth data for a full range of autonomous driving scenarios. This requires selecting devices or components to be testing including sensors, logging of the reference sensing including video, LIDAR, and GPS/IMU, and comparing for key performance indicators in a simulation and under critical scenario's like weather and light conditions. The use of driving simulation for these evaluations offers several advantages over using test tracks or naturalistic driving:

- Safety and liability risk related to installing prototype systems in actual vehicles
- 24/7 availability regardless of weather
- Quickly reconfigure vehicle operation to enable within-subjects experiments
- Reliably reproduce same driving condition for all subjects
- Provide experimental control to draw causal conclusions that cannot be drawn from observational and naturalistic data.
- Motion provides dynamic for the partially automated systems that cues that either startles driver into wanting to take over control, or can signal to driver that system has disengaged (e.g. they can feel the vehicle slowing down or drifting out of the lane)

The following are high priority research activities cited in the survey for testing and evaluation:

- Develop data capture and retrieval techniques including instrumented vehicles with data acquisition systems (DAS) for driving on test tracks and on public roads. The DAS architecture should be linked to standardized performance measures. The instrumented vehicle should also be able to support custom engineering tests (ISO 7401, ISO 4138, ISO?TR 3888) at a wide range pf settings (e.g., steering angle, speed, throttle positions, etc.).

- On-road testing of highly automated vehicle performance is limited by safe practices used by the automakers and their suppliers. A procedure and a set of performance criteria should be established for making the decision to move testing from the test track to public roads.
- Develop a process for determining and specifying acceptable levels safety and reliability for automated vehicles.
- Develop hardware in the loop as standard practice for testing automated system components and integrate the bench-top tools with simulations of vehicle dynamics and microscopic traffic models.
- Examine the use of modeling and simulation over all operational scenarios
- Examine human responses to failure modes (single and multiple) and to cyber threats.
- Create a methodology for safe testing with human in the loop including simulation, driving on a test track, and driving on public roads including naturalistic driving.
- Address the energy and environmental impacts of selected automated features and the overall impact for full automation.

Automated Vehicle Science, Technology, and Engineering

We asked our panel of experts to provide us with their highest priority research and development challenges in the area of automated vehicles. This question generated many ideas that we have attempted to organize into three categories: scientific challenges, technology challenges, and engineering challenges. The input from the panelists was relatively unstructured and many of the panelists identified similar topics and issues. We have tried to combine them to eliminate redundancies. The topics are not listed in any particular order. However, we did try to separate issues that were immediate, or within the next five years, and those that were long term, or requiring beyond five years to address and accomplish.

Automated Vehicle Science

Next Five Years	Beyond Five Years
• New wayfinding and shortest path algorithms for computationally efficient if not optimal computation of vehicle trajectories • Development of artificial intelligence approaches for computer vision algorithms including stereo and night vision • Since one of the primary objectives of self-driving vehicle is to detect and recognize unusual but critical objects in the field of view, for example, a ball or balloon that could suggest a child is following behind, more research needs to be devoted to identifying and achieving high detection rates for anomalous "outlier" objects without also generating unacceptable numbers of false-positive detections. • Modeling vehicle behaviors and maneuvers in real-world vehicle environment while addressing gaps between requirements and models, and integrating heterogeneous models representing	• Modeling the relationship between the driver and the automated vehicle including the notion of "teamwork." • Resilience as dependability in presence of changes including new model vehicles in mixed traffic experiencing unforeseen events and failure modes. This also includes resilience to evolving user requirements, changing operating environment, and scalability challenges. • Develop full automation architecture that supports adaptive graceful degradation • The best system architecture for automated vehicles has not yet been identified. One of the highest priority research issues that need to be addressed at this point is the system architecture for automated vehicles that identifies machine-to-machine (M2M) communication interfaces supporting interoperability.

Next Five Years	Beyond Five Years
different aspects of the system behavior. • New sensors that will operate under all environmental climate extremes • Develop simulations for testing and evaluating vehicle to vehicle behavior in merging, lane centering, and lane changing maneuvers on both highways and surface streets	

Automated Vehicle Technology

Next Five Years	Beyond Five Years
• Conditional automated vehicles for fail-operational autonomy in exit-to-entrance highway environment with surround sensing, driver monitoring, perception and localization, real-time decision and maneuver processing, fault tolerant motion control. • Improved high-speed computer vision algorithms for static and dynamic object classification detection in complex environments along with improvements in performance and reduction in cost of graphic processors. • Multi-sensor fusion and integration for improved perception including V2V and V2I communication • Health maintenance systems designed to detect faults and recover from general hardware and software failures • Software for obstacle avoidance and other maneuvers to manage the highway environment • Methods of communicating with automated vehicles need to improve and can with the possible adoption of natural language and higher resolution display technology. • Continuous work on reducing component costs and improving component reliability including sensors, image processors, integrated circuits, data buses. Continued cost reductions in LIDAR if this is to be part of the sensor suite. •	• Fully automated vehicles with the following features: surround sensing, multi-sensor fusion, driver monitoring, perception and localization, real-time decision and maneuver processing, robust and expandable architecture supporting interoperability, fault tolerant motion control • Software for obstacle avoidance and other maneuvers to manage the surface street and general urban transportation environment • Development of the optimized "no-stopping" intersection will require both vehicle centric control for variable speed platooning and centralized coordination of intersection signalization. • Continuous work on reducing component costs and improving component reliability including sensors, image processors, integrated circuits, data buses. Continued cost reductions in LIDAR if this is to be part of the sensor suite.

Automated Vehicle Engineering

Next Five Years	Beyond Five Years
• Developing systems for pedestrian and dynamic object detection, classification, and avoidance • Coordination of vehicles and the traffic control infrastructure with the goal of improving traffic	• Designers should be able to adopt lighter materials and eliminate some of the structural safety features of the vehicle when the likelihood of crashing has been reduced.

Next Five Years	Beyond Five Years
flow and overall throughput while maintaining safety including CACC, cooperative and adaptive signals, and convoys and platooning • Develop the optimal system architecture for automated vehicles that identifies machine-to-machine (M2M) communication interfaces supporting interoperability. • Exceedingly reliable integrated physically redundant surround sensing with active measurement and object classification • Develop methods and facilities for verifying and validating automated and connected vehicle systems on the test track and on road environments. • Improve driver assist and active safety functionality and the prospects of a crashless vehicle with a goal of zero fatalities in 10 years and minimum injuries and property damage. (2.24 M injuries, 32 M fatalities 2010 NHTSA) • Start 3D mapping of highways and high-volume surface streets in selected jurisdictions adopting higher levels of automation • Managing driver distraction will be an early challenge in the development of automated systems to be replace by transitioning from engaged to not engaged and occupied with other activities, • Extension of and compliance with ISO 26262 and SAE guidelines on functional safety to determine risk classes and to specify automotive safety integrity levels (ASILS) dealing with both safety and security requirements. • Adoption of Autosar, FlexRay, and other emerging software standards in vehicle networking	• Moving from driver assist to higher levels of automation requires redundant system design featuring high reliability, fault tolerant, and fail safe designs. • Develop approaches to operational vehicle capability prototyping to support flexible and robust is a flexible evaluation of new systems and technologies, stimulating design teams and exploring the realm of the possible without needing an early commitment to procurement. • Fully 3D mapped road network environments including all highways and surface streets for each nation adopting fully automated vehicle systems that is precise and up-to-date all of the time • Continuous work on reducing system costs and improving system reliability • Continuing extension of and compliance with ISO 26262 and SAE guidelines on functional safety to determine risk classes and to specify automotive safety integrity levels (ASILS) dealing with both safety and security requirements.

Connected Vehicles

Information and communications capabilities in vehicles can make travel safer and more efficient by providing real time, hands free information to drivers. Telematics today can calculate the most efficient travel route, avoid traffic, assure that an emergency response comes quickly, and point to the nearest available parking spaces, fueling locations, or other desired destinations. In the near future advanced telematics will be increasingly hands-free and will enable commuters to reserve parking places at high tech transportation hubs, reserve seats on buses, car pools, van pools and company transit options. Telematics also enable new usage-based insurance options that set rates based on car use and driver behavior. Finally, advanced telematics can enable variable road pricing that will reduce peak congestion and provide a more sustainable and fair method to pay for maintaining relatively expensive urban road systems. Advanced telematics will provide more flexible and accessible transit options into and around urban areas and help to intercept single occupant vehicles with easy-to-use transit options before SOVs enter core congested urban areas, increasing urban transit use and reducing pollution.

In their book Reinventing the Automobile the authors show how dynamic pricing combined with intelligent vehicles enable drivers to respond to the pricing of resources including road space, parking space, vehicle fleets, and insurance (Mitchell, et al., 2010). Dynamic pricing provides many advantages including a sound basis for rational individual decision-making and optimization of overall system behavior. For the individual driver pricing can reflect the total cost of the trip very accurately and enable travelers to make choices among alternative modes, departure times, roots, and destinations. For the urban system a fee helps the management of available urban space and infrastructure and a means to compensate for social equity and other policy objectives. Vehicle electronics and communication systems provide the technology needed to implement pricing to increase efficiency and potentially provide revenues for public goods and markets with real business opportunities.

The onboard communication capability includes cellular, Dedicated Short Range Communications (DSRC), Wi-Fi and Bluetooth technologies. The primary attractiveness of commercial cellular continues to be maturity of technology and significant 4G coverage, including for most major urban areas, suburban areas and even significant coverage of rural areas. Commercial wireless and Wi-Fi technologies continue to show promise for providing secondary, tier-two services associated with the Connected Vehicle. DSRC is primarily used to enable vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) active safety and autonomous driving systems. DSRC is currently limited to approximately 1200 feet, line of sight, and will require significant investment in new infrastructure. (Arumugam, et al., 2013; Delgrossi Zhang, 2012).

Each vehicle will need a V2V and V2I communication system to assist in tracking the vehicles, enabling vehicle platooning, and triggering the road crossing signals. It also provides a conduit for real-time transmission the data for evaluating the performance of the entire system. The communications system architecture is based on the Intelligent Transportation Systems National Systems Architecture that is presented at a high level of abstraction in Figure14.

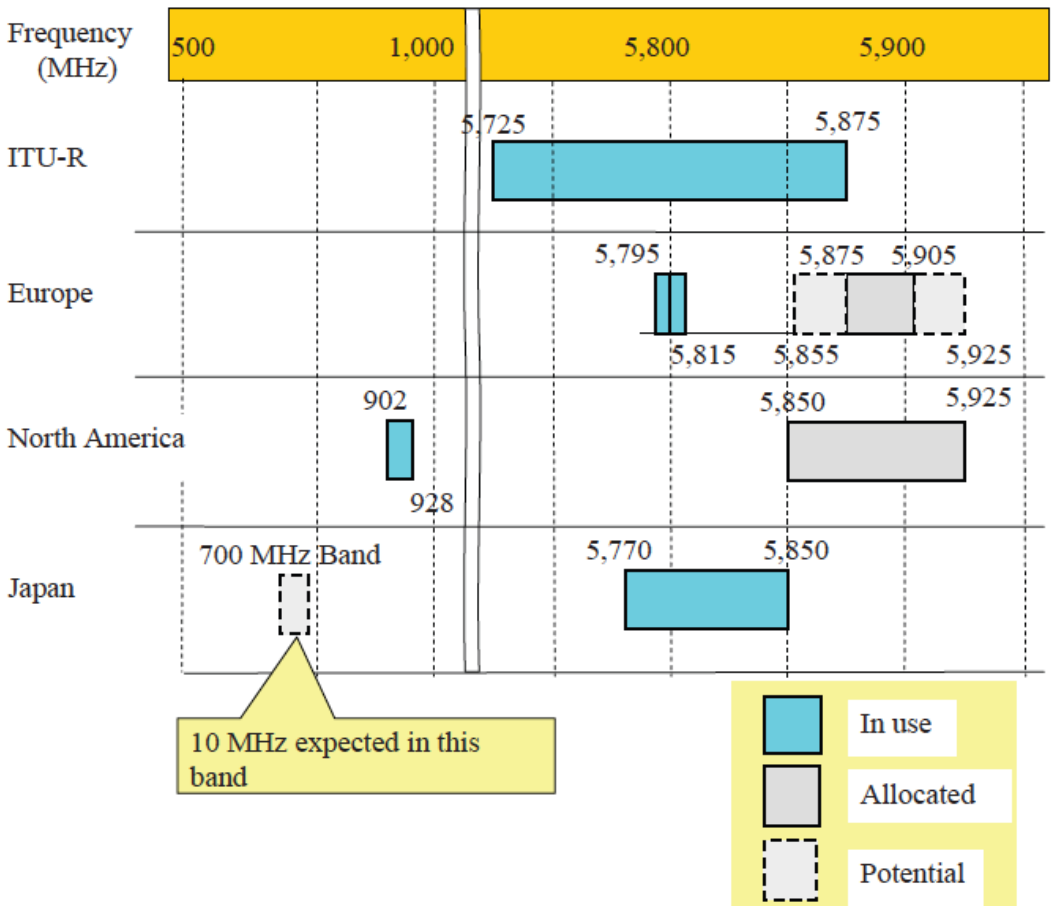


Figure 13. DSRC Frequency Allocation in North America, Japan, and Europe (Oyama, 2009)

Generally vehicular networks are considered to contain two types of nodes; vehicles and roadside stations. Both can be implemented as DSRC devices. The network should support both private data communications and public (mainly safety) communications but higher priority is given to public communications. Vehicular communications is usually developed as a part of Intelligent Transport Systems (ITS). ITS seeks to achieve safety and productivity through intelligent transportation which integrates communication between mobile and fixed nodes. To this end ITS heavily relies on wired and wireless communications. (Chan, 2011)   The following are the most common active road safety applications being addressed in foeld trials and the safety pilot: intersection collision warning, lane change assistance, overtaking vehicle warning, head-on collision warning, rear end collision warning, cooperative forward collision warning, emergency vehicle warning, free crash sensing and warning, cooperative merging assistance, emergency electronic brake lights, wrong way driving morning, stationary vehicle warning, traffic condition warning, signal violation warning, collision risk warning, has this location notification, and control loss warning (Karagiannis, et al, 2011).

The 75 MHz band in the 5.9 GHz (5.85-5.925 GHz) frequency range allocated by the FCC offers significant data transfer capacity with bandwidth of 75 MHz and approximate range of 1000m. However, to make use of this spectrum in a mobile environment required development of new communications protocols. The core radio protocol used is based on the well-known IEEE 802.11a/b/g wireless Ethernet standard, often referred to as Wi-Fi. Because of the unique mobile environment, the IEEE 802.11a standard was modified to allow what is known as an "association-less" protocol, identified as IEEE 802.11p. This means that the system does not establish a conventional network with all of the mobile terminals as nodes, all of which know about each other. (Weigle, 2008)

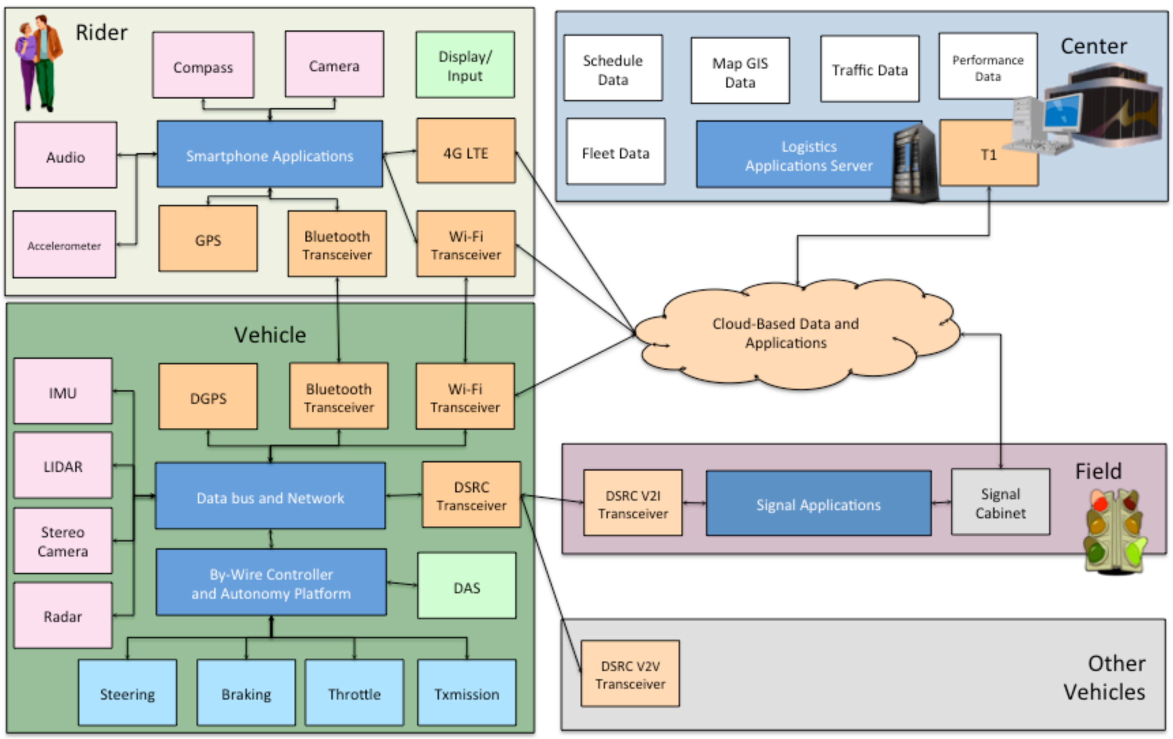


Figure 14. High Level Communications Architecture

IEEE 802.11p is an approved amendment to the IEEE 802.11 standard to add wireless access in vehicular environments (WAVE). It defines enhancements to 802.11 (the basis of products marketed as Wi-Fi) required to support ITS applications. This includes data exchange between high-speed vehicles and between the vehicles and the roadside infrastructure in the licensed ITS band. (Li, 2012)

It is expected that the autonomous vehicles will be 'connected' via DSRC when they are in close proximity with each other (typically within 300m). Autonomous vehicles will also be expected to connect wirelessly, via DSRC, to infrastructure devices such as traffic signal controllers when they are within 300m range to such intersections. The exact V2V and V2I over the air message contents will be defined in accordance with the current SAE J2735 and SAE J2945 standard guidelines and as required by the final vehicle autonomous features. IEEE 1609.2 standard security layer protocols are used for all DSRC communications, while IEEE 802.11p standards are used for lower layers. (Shulman & Deering, 2007)

IEEE 1609 is a higher layer standard based on the IEEE 802.11p. 802.11p will be used as the groundwork for DSRC, a U.S. DOT project based on the ISO Communications, Air-interface, Long and Medium range (CALM) architecture standard looking at vehicle-based communication networks, particularly for applications such as toll collection, vehicle safety services, and commerce transactions via cars.

The on-board equipment (OBE) is a self-contained computing system that supports a wide variety of applications and services. It will be used in a vehicle, although it is also capable of bench-top operation. It was not intended to be a deployable platform but as a test platform for use in the POC.

The OBE computing platform hardware is the central piece of hardware responsible for vehicle interactions within the DSRC network. The hardware supports communications with other DSRC components, exchanges data with Original Equipment Manufacturer (OEM) vehicle systems through a Controller Area Network (CAN) interface, and accommodates driver interaction through a HMI. In addition to providing the hardware implementation of OBE interfaces for the POC, the OBE computing platform hardware also provides daughter card slots and assorted local interfaces which provide feature, control and test flexibility during POC. Figure 4 provides a diagram showing the OBE computing platform hardware within the context of the POC vehicle and related VII components. (Rakouth, 2013)

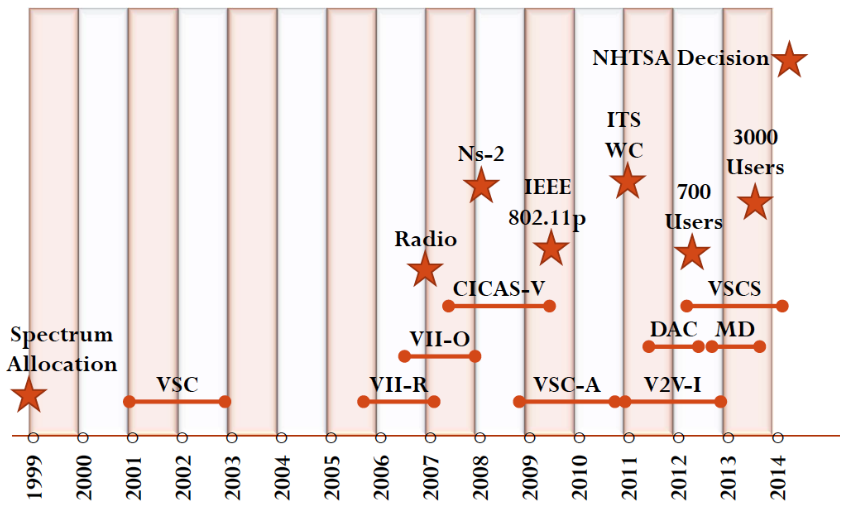
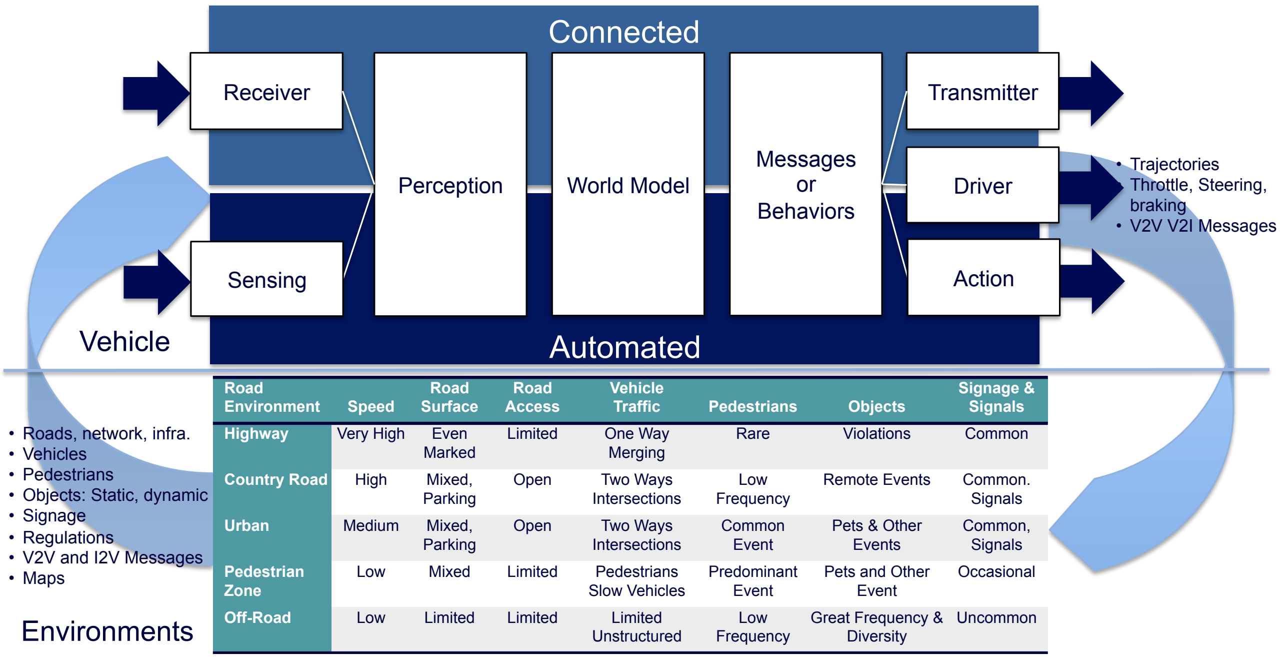


Figure 15. 5.9 GHz DSRC Milestones (Delgrossi, 2014)

The reason this is not done is that the mobile terminals (OBEs in the POC) are entering and leaving the hot spot rapidly, and there is insufficient time available to set up a new network identity for each new arrival, and inform all other nodes in the network before the network changes again because a terminal has left the footprint of the road-side equipment (RSE), or a new one has arrived. On the surface, this approach may seem to limit the functionality of the system since it means that any given mobile terminal cannot interact uniquely with another terminal (the way computers on an office network might), but this is not the case. Because the system is radio based, all terminals can hear all messages sent. Since, under most circumstances one can simply broadcast a message in the local area, and all terminals (OBEs and RSEs) can receive it, there is no need to establish a unique low-level network identity for each communicating device. (Sichitiu & Kihl, 2008)

Connected Assist and Safety

While the USDOT Safety Pilot in Ann Arbor demonstrated the potential safety benefits of alerting drivers to imminent risks and hazards, especially those outside the drivers' line-of-sight, in the not too distant future V2V and V2I capabilities will be integrated with active safety technologies that will automatically intervene and prevent accidents from occurring. One example of possible near-term implementation of V2V warning is Emergency Electronic Brake Lights (EEBL) that transmits a signal to following vehicles if the driver is forced to brake hard and suddenly. The warning alerts could take the form of flashing LED lights in the dashboard or rearview mirrors, audible warnings, or haptic feedback in the driver's seat. In the longer term V2V and V2I will help increase the overall coordination of vehicles by controlling for improved flow of traffic and increased throughput in the road network. For example, in the case of EEBL the vehicle might brake automatically if the driver does not respond or it could simply maintain a safe distance. NHTSA predicts that V2V combined with other perception sensors will help drivers avoid or mitigate crashes in 80% of the vehicle crash scenarios involving unimpaired drivers.



Road Environment	Speed	Road Surface	Road Access	Vehicle Traffic	Pedestrians	Objects	Signage & Signals
Highway	Very High	Even Marked	Limited	One Way Merging	Rare	Violations	Common
Country Road	High	Mixed, Parking	Open	Two Ways Intersections	Low Frequency	Remote Events	Common. Signals
Urban	Medium	Mixed, Parking	Open	Two Ways Intersections	Common Event	Pets & Other Events	Common, Signals
Pedestrian Zone	Low	Mixed	Limited	Pedestrians Slow Vehicles	Predominant Event	Pets and Other Event	Occasional
Off-Road	Low	Limited	Limited	Limited Unstructured	Low Frequency	Great Frequency & Diversity	Uncommon

Figure 16. Automated and Connected Vehicle System

Driver warnings are one of the primary categories of driver assist functions supported by connected vehicles. Many of the vehicle-to-vehicle applications for connected vehicles provide warnings to the driver about maneuvering outside the safe zone of operation. So, for example, if the driver attempts to change lanes on the highway this passes slower vehicle and the driver turns the steering wheel without looking the sensors to provide a warning to the driver if that an equipped vehicle is detected in the blind spot. If the connected vehicle is moving into an unsafe zone relative to other connected vehicles and objects the driver gets warning.

The thing about connectivity is this only works for connected vehicles that detect other connected vehicles and/or connected "things." in its detection environment. An "unequipped" vehicle or pedestrian cannot be detected directly by connected vehicle. So, with regard to safety and especially collision avoidance the connected vehicle technology is only as good as the level of adoption. As the level of adoption increases so does the safety associated with connected vehicles. Unfortunately, it is unlikely that everything, let alone all vehicles, will ever be connected, and this limits the safety impact of connected vehicle technology.

Whether this limitation on the connected vehicle's driver assist functionality is acceptable as a competitor with or supplement to other line-of-sight vehicle sensors like cameras or radar is more of a market or policy question than it is a technology question. Similarly, the question about increasing the adoption rate by mandating connected warning systems in new vehicles or regulating aftermarket purchases is a policy issue that that will be made in the context of already increasing levels of driver safety being attained partially because of the market growth in driver assist.

This discussion about warning systems also calls into question the value of collision warning in the context of vehicle automation. Presumably the self-driving vehicle will not sound off warnings to the passenger of imminent collisions or their maneuvers to avoid them. This is not to suggest that vehicles will soon be operating only in automated modes. In fact, much of the time vehicles with driver assist functionality or vehicles that are partially or fully automated will indeed have human drivers. So, when the human drivers behind the wheel warning systems will be helpful. Furthermore, out survey suggests that the widespread adoption of partially or highly automated vehicle technology will not take place for a couple of decades. In the meantime when the driver is in control it may help to keep him or her alert. The point is that if warning systems are set to detect vehicles or object outside the safe range of operation than they should not trigger warnings for safely operated automated vehicle. Rather, the role for potentially longer-range detection functionality of the communication system will be to alert the automation system and assist in the coordination of the vehicles and the infrastructure.

Safe and efficient flow of connected vehicles requires extraordinary coordination of vehicles where intelligence and control is distributed to individual vehicles in the road network. Each vehicle, or the driver of the vehicle, operates autonomously and yet will coordinate with other vehicles in their immediate vicinity within the network. Because of this distribution of decision making and activity among the vehicles research will be needed on the coordination of the vehicles and the traffic control infrastructure with the goal of improving traffic flow and overall throughput while maintaining safety. Some of the more familiar forms of coordination that are already being addressed include cooperative adaptive cruise control (CACC), cooperative and adaptive traffic signals, and convoys and platooning. A more advanced research topic in the cooperative planning of vehicles to reduce or eliminate delay time at intersections. V2V and V2I will assist in identifying gaps for entry into intersections and coordinating platoons through the intersections.

While some of these topics like CACC focus on relatively independent of coordination of vehicles through vehicle-centric control. Other topics, like signal coordination, involve more centralized control of traffic. An optimized "no-stopping" intersection will require both vehicle centric control for variable speed platooning and centralized coordination of intersection signalization.

Many of our panelists suggested that the real benefit of connected vehicles in an environment of increasingly safe vehicles with well-designed driver assist and higher automation functionalities will be derived from connected vehicle coordination rather than from driver warnings. The connected vehicle provides an ability to coordinate vehicles in traffic and to provide information that will enable the automated control systems to maneuver the vehicles more precisely and with greater anticipation than the human driver ever could. So, for example, vehicle connectivity provides inter-vehicle communication and enhanced machine-to-machine automation functionality that will enable vehicles to travel closer together and safely in traffic than what the human driver could ever manage without putting them at serious risk. This can potentially increase throughput on freeways, coordinate vehicles at signalized and non-signalized intersections, assist in the platooning of vehicles and thereby reducing drag and increasing fuel efficiency, and perhaps further into the future coordinating networks of vehicles for improved mobility, safety, and overall efficiency. At least that is the promise of vehicle to vehicle and vehicle to infrastructure communication systems in the long term. In the short term the connected vehicle can assist by providing driver warnings about other connected vehicles, assist by providing redundancy and early alerts to the automated driving systems, and coordinate with other connected vehicles in cooperative systems like platoons with shorter headways and convoys.

It is the immediate benefit of systems like platooning and long term benefits of complete coordination at high levels of adoptions in populations of highly automated vehicles that perhaps provides the greatest justification for public policy to mandate connected vehicle technology around a national (or international) communication standard. Should such a policy go into effect at a national level and then some states require aftermarket devices then the technology will still take decades to reach higher levels of market penetration. However, in the meantime some lives will be saved, some drivers may get enjoy the benefits of convoying, and there will be a promising future of higher levels of highly coordinated road transportation.

One of the most significant research challenges will be to implement public systems that will accept or work around vehicles that do not have connectivity. For example, EELB works fine for vehicles that are connected. However, EELB-equipped vehicles cannot communicate with vehicles that do not have a radio receiver. The same will be true of all communications based vehicle coordination systems including leader-follower systems and coordinated signaled intersections.

It is clear that voluntary systems for vehicle coordination like platooning among equipped vehicles will be implemented early if there is adequate demand because they do not require full market penetration to assist the equipped vehicles. By contrast even if there is a mandate the V2V-based collision warning and avoidance systems may come later because their value depends on market penetration of the "here I am" messaging.

The highest priority research topic related to connected vehicle systems is Cybersecurity. This is addressed at length in the section devoted to this topic. Yet perhaps the most important near-term use of V2I systems will be the continuous updating of digital maps used for sensor-and-map-based localization. However, digital map updating is likely to be provided through subscription upon purchase and available through digital cellular communication.

Table 3. Expert Forecast of Cooperative Automated Systems

Passenger Vehicle market introduction	Median	Interquartile Range		Mandated	Government Pilot
Cooperative Adaptive Cruise Control	2020	2018	2020	5 yes 15 no	10 yes 10 no
Autonomous Intersection Assist	2022	2020	2025	8 yes 12 no	16 yes 4 no

Finally, a future with higher levels of adoption of connected vehicles could also be coordinated with and provide some technology alternatives for automated connected road pricing which is discussed in more detail in other sections of this report.

Connectivity and Cybersecurity

Cybersecurity is concerned with the defense against attacks on information technology, operation technology, and networking and communications systems infrastructure and is a major concern for government and the private sector. While hardware security is of course of interest here, perhaps the primary source of vulnerability is the software in applications, devices, and networks. Common technologies that everyone is familiar with such as firewalls and antivirus software help to secure critical infrastructures against cyber attacks but additional research is needed on the Cybersecurity of automated and especially connected vehicle systems.

The completely connected automated transportation system will not only require security measures for vehicle hardware, software, and communications but it will also require security for remote information technology systems where, for example, digital maps are maintained and updates are transmitted to vehicles to keep the localization systems up to date.

Vehicles that feature communication systems for controlling the vehicle will require credential management to ensure the integrity of safety data being transmitted. These systems will not only need to thwart attacking adversaries through real-time operational intelligence but they will also need to manage vulnerability through authentication and access control and mitigate risk by reducing exposure. Furthermore, the system designers will need to take a lifecycle approach to software development to reduce the likelihood that vulnerabilities are introduced through the product development process.

System attack vulnerabilities are not only a concern for telematics systems but they are especially critical design considerations for connected active safety and automated vehicle control systems. While separation of the entertainment and information features from the vehicle control system will help to manage this vulnerability, the integration of connected vehicle control functionality remains a major concern from the perspective of Cybersecurity. One of the major advantages of environment perception sensors like radar, lidar, and cameras is the inherent access limitation they provide.

- Some of the issues that need to be addressed in the area of Cybersecurity for active safety, driver assist, and higher levels of automated vehicle systems include: secure system an
- Separate and isolate the vehicle controls, including braking, steering, transmission, and throttle, from the telematics and V2V and V2I connected vehicle systems. This implies that the connected vehicle systems will have a limited role in active safety and vehicle automation.
- Devote great care to assure the security of updating of the digital mapping system used for localization and static versus dynamic object identification.
- Extension of and compliance with ISO 26262 and SAE guidelines on functional safety to determine risk classes and to specify automotive safety integrity levels (ASILS) dealing with both safety and security requirements.
- Improve and use software development lifecycle processes and structured coding techniques to identify and limit coding errors earlier in the process
- Adopt next-generation high-performance simulation and computing technologies to assist in the efficient validation of software performance
- Advance the state of the art in authentication, credential management, and access control strategies for software installation, maintenance, and operation.
- Design the vehicle network and communication system to anticipate and mitigate cyber related disruptions to ensure resiliency while maintaining privacy and reliability.

DSRC-Based Connectivity

Round 1; Question 4: What role will DSRC-based vehicle connectivity have in vehicle automation in the United States?

DSRC based connected vehicle technology is hot discussion topic these days in many professional circles such as USDOT, OEMs, suppliers, engineering consulting firms, and so on. The opinions expressed by the experts in this survey are found greatly interesting. The following summarizes what the majority have explained in their response:

- DSRC based connectivity realistically is far from the lowest hanging opportunity to reduce crashes. OEM's will be deploying more advanced safety features on-board each automobile year after year. These safety technologies are used for numerous increased safety functions (i.e. automatic emergency braking, lane change assist, lane keeping, cross traffic alert, blind spot monitoring, pedestrian detection, etc). Hence, given the progressive of path of deploying on-board sensors that are the building blocks of automation/autonomy, V2V is deemed to be playing an only complementary role by providing another source of information for redundancy. However, some vehicle automation applications (e.g. Platooning) are expressed as exceptions where V2V is a major enabler.

- The second major theme found among the responses was that V2I plays a greater role in enabling vehicle automation, as opposed to V2V. V2I will become a multi-facetted tool for automation that will be more and more appreciated. This is will be driven by opportunities such as "green-wave" applications, navigation and positioning in GPS denied areas, providing map data, and even expanding its foot print in protecting vulnerable road users.

Analyzing the responses, as mentioned before, the majority of respondents believed V2V offers little value in enabling the vehicle automation while V2I can take the vehicle automation to the next level by unlocking many of its capabilities.

Cellular-Based Connectivity

Round 1; Question 5: What role will 4G LTE and general telematics have in vehicle automation in the United States?

With exception of two panelists who mentioned LTE (or other types of cellular communication) plays no role in vehicle automation, other panelists unanimously pointed out that LTE will be essential in accomplishing two main objectives: 1)real-time delivery of digital map data and providing look-ahead information (e.g. icy roads, work zones, etc) and, 2) Over the air software updates for automated vehicles.

These two functions (i.e. OTA updates and Digital Map Delivery) are expressed as the main roles of cellular-based connectivity for enabling Level-3 and Level-4 vehicle automation. Nevertheless, other applications such as location based services (LBS) or infotainment are also mentioned by the panelists, but not as enabling applications.

Manual Override

Given the capabilities of a Level 4 automated vehicles, panelists were asked about their opinions if such vehicles should feature a manual override button or mechanism. Unlike the previous questions in which respondents demonstrated nearly a uniform response, in this case there is a split where two thirds of the respondents believed implementing a manual override is a must whereas a third of respondents were of the belief that it depends.

- Majority respondents who believed featuring a manual override is a must for automated vehicles, their reasoning was based mostly on either a) giving the driver the ability and confidence of taking over the control of the vehicle operation in case of an failure or accident and b) providing the driver with the choice of fun in driving the vehicle manually.
- The remainder of the respondents believed providing (or not providing) a manual override depends on several factors and conditions: a) in an environment where there are sufficient reliable Level 4 vehicles, it's best not to provide manual override in order to increase the order in the overall system. b) As technology capabilities grow from semiconductor technology advancements, more redundancies can be added, which limits the need for override. c) A manual override is potentially very dangerous, as the driver might react improperly. So a true manual override is a bad idea. However an override "request "is fine, where the driver requests to regain control and the system responds if appropriate and safe. This means an extensive protocol will have to be established to ensure safety especially during automated evasive maneuvers like a double lane change during obstacle avoidance.

Connected Vehicle Science, Technology, and Engineering

The expert survey did not focus as much on issues specific to the connected vehicle, including vehicle to vehicle and vehicle to infrastructure communication systems, rather, the connected vehicle was addressed as part of the broader automated vehicle system where the radio is essentially another sensor picnic communications from other vehicles, roadside devices, and possibly from "here I am" devices carried by pedestrians. As a result there is a smaller number of science, technology, and engineering issues identified by our panel for connected vehicles. Nevertheless, there was a sufficient number for us to break out the topic of connected vehicles as a separate item and to report on the results in a separate section. The science technology and engineering issues for connected vehicles are listed in the tables below. Many of the research issues identified in the automated vehicle section of this report also pertain to the connected vehicle.

Connected Vehicle Science

Next Five Years	Beyond Five Years
• Higher levels of cooperation among vehicle supporting network level coordination of vehicles through intersections in order to minimize stops and delay. • Develop simulations for testing and evaluating vehicle to vehicle behavior in merging, lane centering, and lane changing maneuvers on both highways and surface streets	• Integrating with and leveraging automated vehicle sensors like radar, lidar, and vision to increase the performance of the vehicles in specific maneuvers as well as extending the capabilities of the vehicle through communication with more remote objects. • Modeling and simulation of intersection, lane changing, vehicle passing, and other traffic behaviors and maneuvers for connected vehicles and their interaction with other connected vehicles, automated vehicles, and unequipped vehicles to reduce crashes and increase throughput.

Connected Vehicle Technology

Next Five Years	Beyond Five Years
• Development of V2V control systems that will accept or work around vehicles that do not have connectivity. V2V will be integrated with line-of-sight vision and radar systems. • Develop and finalize interoperability testing and compliance standards for short-range communication for V2V and V2I. • Develop the V2V and V2I transceivers that meet the standards transceivers mandated by NHTSA. • Conducting field tests for cooperative adaptive cruise control, to evaluate the potential for improving network flow. • Develop improved automated scenario generation tools that have advanced offline processing capabilities for reference sensing and simulation of critical scenarios.	• Development of the optimized "no-stopping" intersection will require both vehicle centric control for variable speed platooning and centralized coordination of intersection signalization. • Continued development of multi-sensor fusion and integration capabilities for improved perception including V2V and V2I communication • Vehicles that feature V2V and V2I communication systems for controlling the vehicle will require credential management to ensure the integrity of safety data being transmitted. These systems will not only need to thwart attacking adversaries through real-time operational intelligence but they will also need to manage vulnerability through authentication and access control and mitigate

Next Five Years	Beyond Five Years
	risk by reducing exposure. • Design the vehicle network and communication system to anticipate and mitigate cyber-related disruptions to ensure resiliency while maintaining privacy and reliability.

Connected Vehicle Engineering

Next Five Years	Beyond Five Years
• Development of V2V and V2I algorithms to assist in identifying gaps for entry into intersections and coordinating platoons through the intersections. • Geographical addressing to extend IP routing and addressing to coordinate with GPS addresses. • Design of algorithms to support forwarding of high-speed high-throughput packet transmissions. • Design systems that effectively leverage IEEE 802.11p packet prioritization along with efficient scheduling strategies to handle messages with different priorities. • Improving the performance of the warning systems including reducing false positives and false negatives in a full range of applications including intersection collision warning, lane change assistance, overtaking vehicle warning, head-on collision warning, rear end collision warning, cooperative forward collision warning, emergency vehicle warning, free crash sensing and warning, cooperative merging assistance, emergency electronic brake lights, wrong way driving morning, stationary vehicle warning, traffic condition warning, signal violation warning, collision risk warning, has this location notification, and control loss warning	• Develop tamper resistant hardware to detect false accident warnings. Research needs to address the verification of the system within the context of the intrusion. • Development of cross layer protocols to improve message delay performance for vehicles that are traveling at high speeds and where connectivity is unreliable. • Develop new geo-casting and broadcasting approaches using cross-layer design to reduce congestion and link disruption. •

Electric Vehicles and Electronics

Although electric vehicles in the general subject of alternative fuels are important components of a sustainable future and transportation, the research and development priorities for electric vehicles is very well developed in the construction of a roadmap for electric vehicles has been accomplished a number of other relatively recent assessments.   For this reason our integrated assessment is focusing more on automated and connected vehicles in the expert survey did not address the topic of alternative fuels are electric vehicles. Nevertheless, this is an essential component of the overall vision and roadmap that we have created therefore we have summarized some of the existing literature and policy perspectives on electric vehicles and alternative fuels (Wiseman, et al., 2013). Electric vehicles are part of an overall portfolio of alternatives including fuel cell, hydrogen, diesel, ethanol, GNC, LPG, hybrids, and the full range of all other alternative fuels.

As mentioned in the previous section electric vehicle uses electric power stored in onboard battery. These batteries can be recharged or swapped with other batteries for sustained power. Plug-in hybrid electric vehicles use small internal combustion engines to recharge the onboard batteries and thereby extend the range they can travel. Electric bills or perhaps most efficient vehicle power options when addressing pre-combustion and combustion efficiency. They're an essential part of any strategy to address sustainable transportation with goals of reducing greenhouse gas emissions, managing energy security and peak oil concerns, and taking it into account the emergence of new technologies. Nevertheless, electric vehicles early part of the strategy to address greenhouse gas emissions because the complete solution requires not only reducing emissions at the tailpipe but also upstream of the smokestack of the power source. Furthermore, the core of the issue with regard to oil dependence and greenhouse gas emissions the high level of energy use per person in the United States. America dwarfs all other nations in energy use per person. And while the notion of peak oil is theoretical at best the fact is that supply will be constrained in the national strategy must consider vehicles that are not reliant upon access to conventional oil. Also, does a matter of national security to enable her management of fluctuating volatile costs of petroleum. Nevertheless, for the electric vehicle strategy to take hold it will require endorsement from the automotive industry, increased battery capacity addressing the range issue, and alternatives for decreasing the cost of energy storage.

With regard to endorsement from the auto industry is clear that the production and market for electric vehicles and hybrid electric vehicles is a dramatic growth path. Annual production of electric and hybrid electric vehicles has grown from a few thousand five years ago to nearly 800,000 vehicles in 2013. Just by way of example, Tesla Motors is the international poster child for electric vehicles with the two-seat Tesla roadster reaching a range of 400 km per charge and acceleration from zero 200 km/h in 3.9 seconds. It is 100% electric with lithium ion batteries and currently sells for a manufacturer's suggested retail price of $109,000 with over 1000 of them delivered to customers in 2013. The future model S sedan is planned to sell at about $50,000.

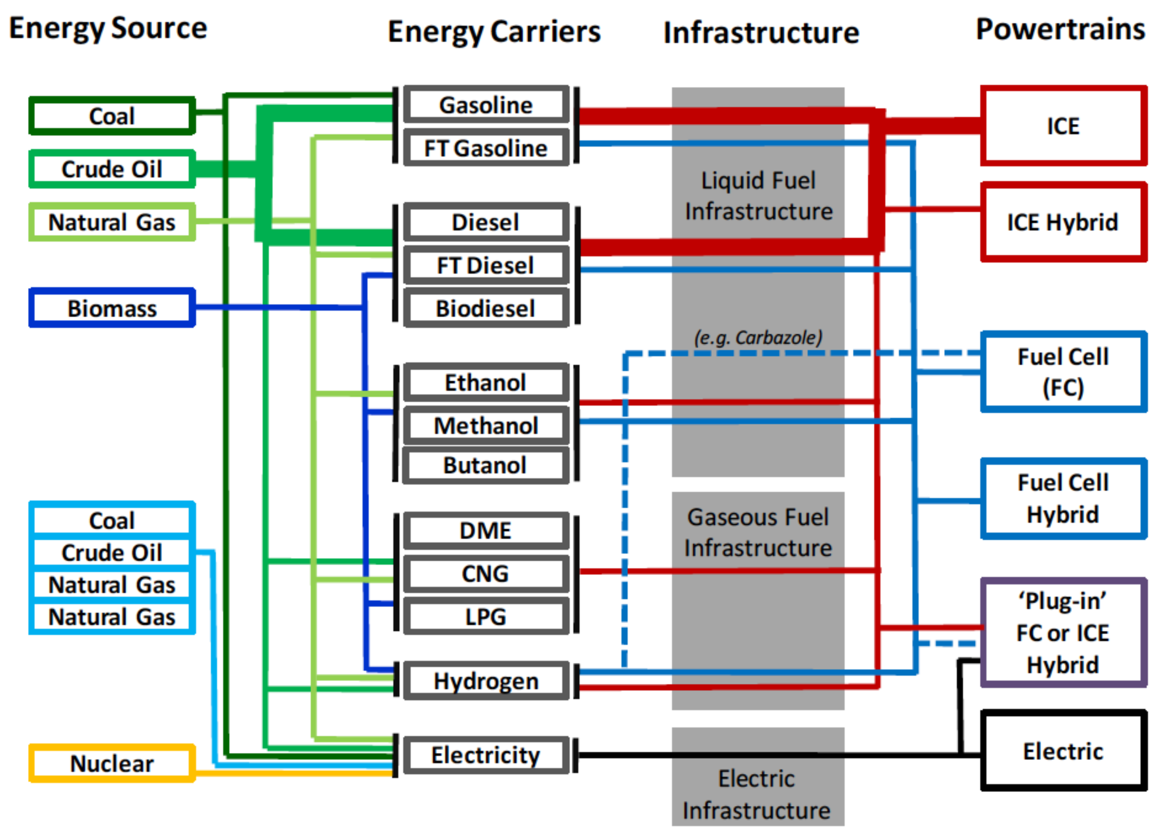


Figure 17. Supplying Energy to Power the Automobile

Lithium-ion batteries have a high-energy storage capacity with a volumetric energy density rating of 315 as far back as 1997 when EV1 was first introduced. By 2007 when the Tesla roadster was first introduced the energy density was up to 580 and it is continual into double every 10 years. Meanwhile the cost of a lithium-ion battery continues to decrease and is now in a very competitive $200 per kilowatt hour (2009).

Automotive manufacturers are facing considerable pressure from environmental mandates, energy security concerns, and societal demands to develop new powertrain technologies that reduce energy consumption and in turn, carbon emissions. At this stage it is difficult to make an economic case for new technologies and national governments are supporting research and development and providing demand-side subsidies. The figure below presents one roadmap for low carbon powertrain technologies for passenger cars. this roadmap shows the progression from the internal combustion engine to hybrids and then toward electric vehicles and possibly fuel-cell vehicles.

The first step in the evolution and all improvements in weight and drag as well as improvements in the internal combustion engine, for example, heat gas recovery. this also involves improvements in structural comp sits, active aerodynamics, and lightweight urban vehicles.

This evolution then involves a second stop with the expansion of hybrid electric vehicles including belt mounted and crank mounted starter generators and small lead acid batteries to store energy. The smaller hybrids will be replaced by full hybrids as the cost of batteries goes down. Improvements in the lithium-ion battery will increase voltage as we approach the year 2020. Some of the enabling technologies will include flywheels and capacitors accompanying reductions in both battery cost and vehicle weight.

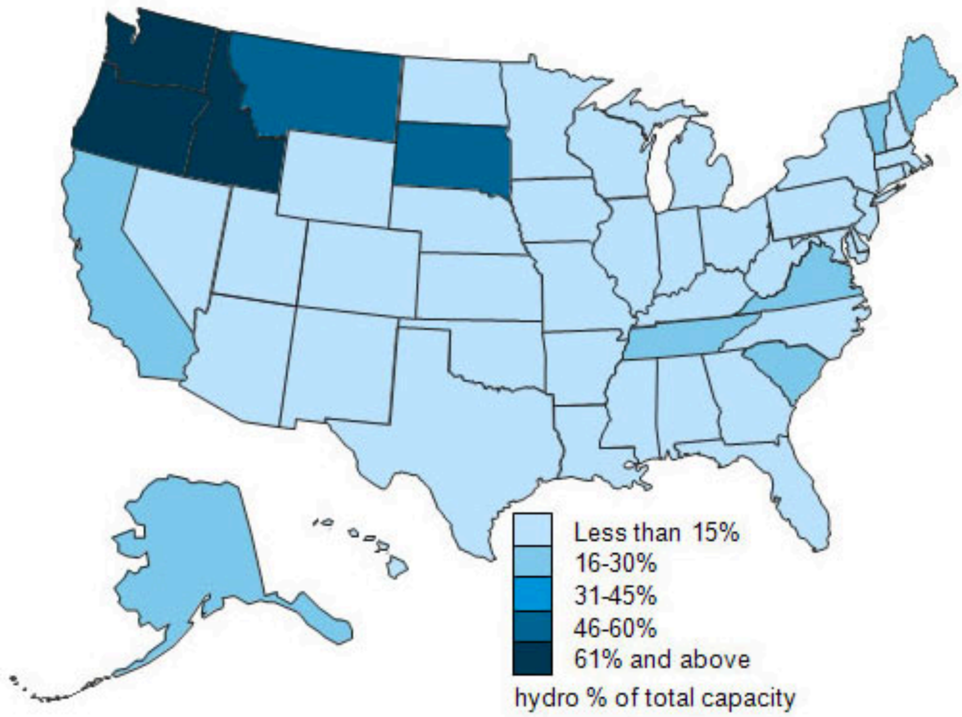


Figure 18. Hydroelectric Power by State, Electric Vehicles Makes Sense in Seattle

The next step involves a transition toward plug-in hybrids and electric vehicles as battery life and cost become more acceptable to the private consumer. The grid supply nead to expand and provides efficient fuel with acceptable level of carbon emissions. subsidies and other incentives are likely to be required in the initial stages.

The next step in market growth for electric vehicles is the charging infrastructure for electricity and possibly hydrogen. This needs to be accompanied by growth in renewable energy to provide a favorable CO_2 balance.

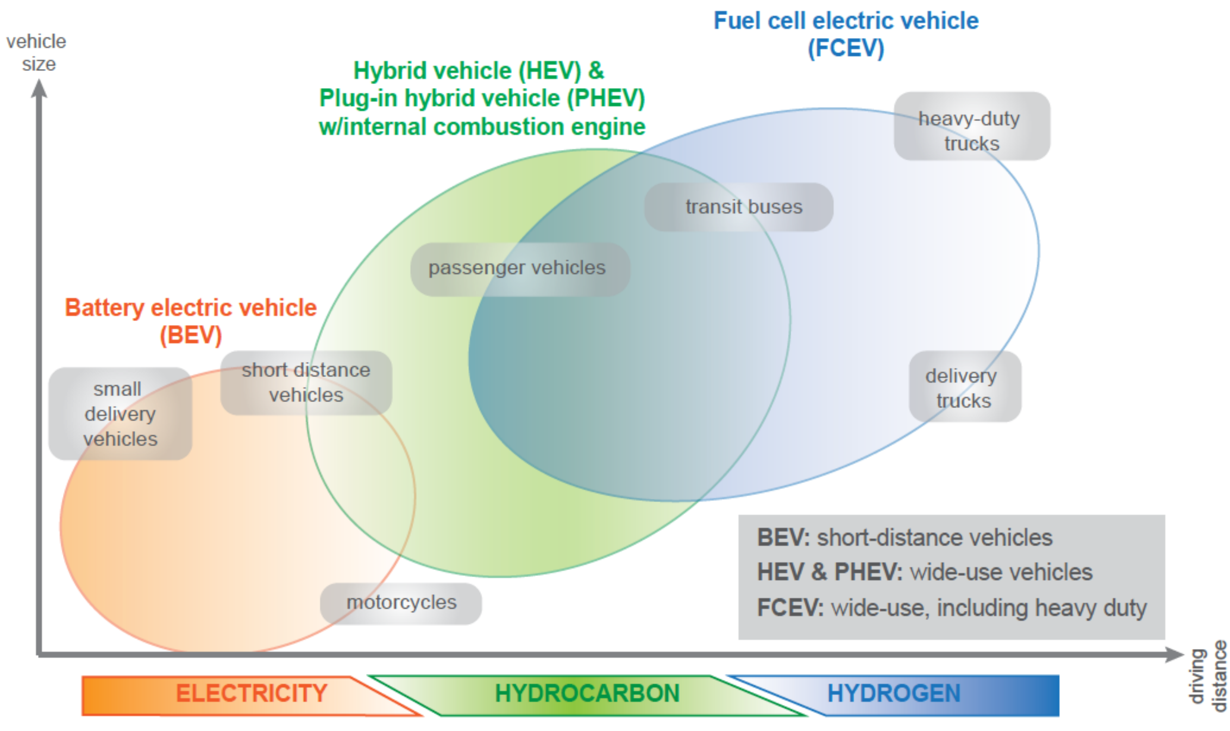


Figure 19. vision of the Electric Vehicle Market

This figure provides a visual overview of electric vehicle market organized by the vehicle size and by driving distance. It takes into account the driving range, the vehicle size, and the energy source of various types of electric vehicles including battery electric vehicles (BEV), hybrid electric vehicles (HEV), plug in hybrid vehicles (PHEV), and fuel-cell electric vehicles. the battery electric vehicles are on the lower left because they are small vehicles that travel short distances. The fuel cell electric vehicle is on the top right of the chart is it offers the greatest vehicle range and vehicle size, from passenger to transit buses and heavy-duty trucks.

So the "goods" on the electric vehicle is that the technology is ready, the auto industry is producing them, and the vehicle has a lower emissions intensity than petroleum. Electricity is ubiquitous in the grid and it supports a national strategy for energy independence. However, there are still challenges or barriers to entry for the electric vehicle including they are more expensive than traditional cars and they seem to require rebates or subsidies to mitigate this cost, many potential customers have issues regarding charging in the range of operation, and if demand continues to grow there's a real concern about the impacts on the national electricity grid.

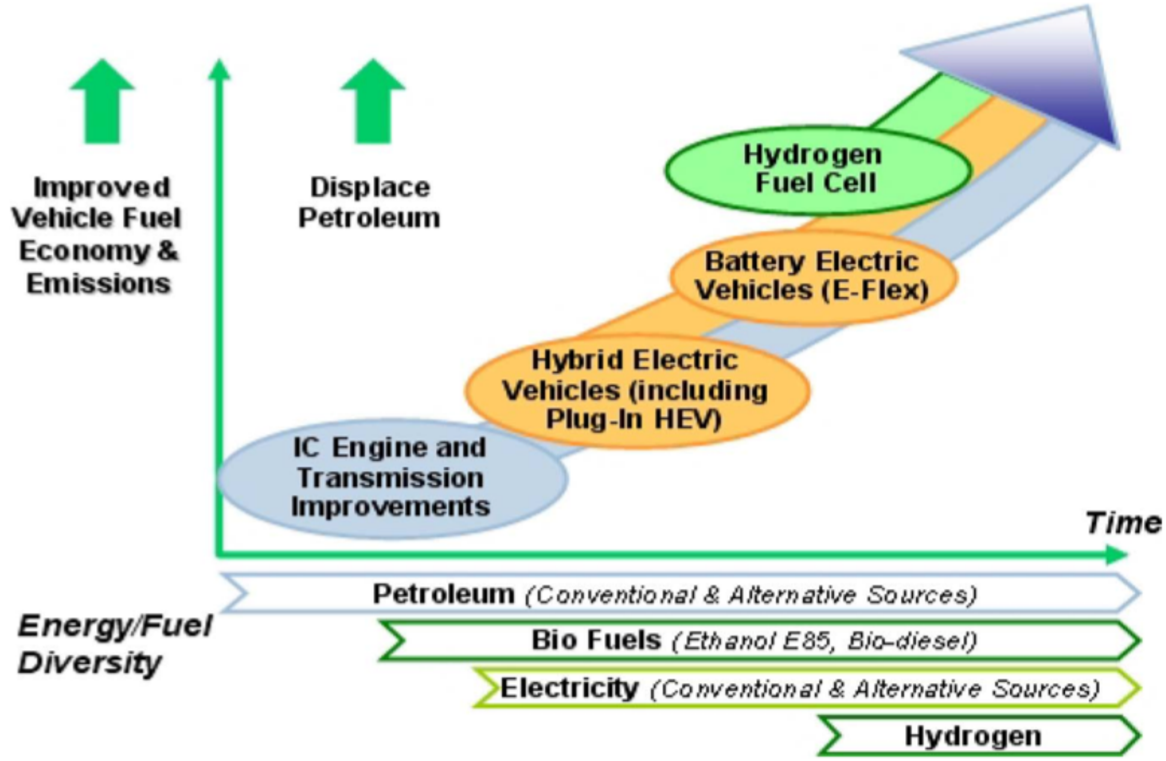


Figure 20. Advanced Propulsion Technology Strategy (General Motors)

Electric motors and electric power are the key enablers for sustainable automotive transportation because of the ubiquity of electric energy and the likely scenario of continuing to decrease costs for batteries and other storage mechanisms. Also, when electric motors are combined with connected and automated "crashless" vehicle systems the fundamental design of a vehicle is transformed enabling lightweight construction of platforms that are essentially powered by a broad range of alternative fuels including hydrogen.

Electric Vehicle Science, Technology, and Engineering

This section describes a number of higher priority research tasks that we identified in the literature on electric vehicles. As in the previous section we've attempted to organize the research and development topics into three categories: scientific challenges, technology challenges, and engineering challenges; and to distinguish between near-term challenges, are those that can be accomplished are addressed within five years, and longer-term topics, say, those that it would be addressed beyond five years.

Electric Vehicle Science

Next Five Years	Beyond Five Years
• Development of new lightweight materials suitable for use in automobiles to extend the range of EVs • Breakthroughs in battery chemistry and configuration toward higher energy capacity and lower cost of vehicle batteries • System theory, modeling, and control of a large-scale multilayered network of networks (e.g.,	• Science in support of renewable, sustainable electric power production. • Advance distributed energy storage (e.g., EV battery)

Next Five Years	Beyond Five Years
transportation network, electricity grid)	

Electric Vehicle Technology

Next Five Years	Beyond Five Years
• Vehicle prototypes using lighter weight, sufficiently strong materials • Packaging of new battery chemistry and configurations into prototype batteries for testing and evaluation • Process improvement for more efficient battery manufacturing • Achieving battery electric propulsion in large vehicles, such as buses and trucks. • Further development of fuel cell electric vehicles and the hydrogen supply infrastructure to fuel them. • Distributed data management and middleware for a large number of EV charging stations • Distributed computing platforms for energy and power management systems • Optimal control strategies on EV charging considering multidisciplinary complexities (e.g., driving behaviors, customer choice, dynamic electricity price) • Communication protocols/infrastructure for public EV charging stations considering cyber security (e.g., resilience, privacy, malicious attacks, and intrusion detection)	Ongoing development of new power generation technologies with low GHG emissions, such as small, standing wave nuclear plants. • 3D printing of lightweight, strong vehicle bodies • Integration of battery-stored EV energy with electric power grids. • Fuel cell EVs emerge as an option, supported by hydrogen refueling infrastructure • Ongoing development of distributed renewable energy generators with zero-carbon emissions • Development of interface management in a completely distributed cyber-physical architecture for EV owners, EV charging station owners, aggregators, utilities, and regulators • Development of high-efficiency wireless charging infrastructure for self-driving and connected vehicles in both stationary and dynamic setting

Electric Vehicle Engineering

Next Five Years	Beyond Five Years
• Implementation of manufacturing process improvements at a large scale to support high volume, low cost manufacturing of vehicle batteries • Eliminating structural weight in efficiently manufactured production automobiles • Ongoing improvement of internal combustion engines spurred by progress in battery and fuel cell electric vehicles. • Development of processes of vehicle battery recycling for secondary uses or safe disposal. • Commercialization of wireless power transfer technology in both stationary and dynamic automobile applications • Deployment of wireless EV charging stations and smart meters at municipal parking facilities	• Battery swap techniques developed for rapid "refueling" of battery EVs. • Standardization and mass deployment of public EV charging stations • Standardization of wireless EV charging stations • Regulation, policy, business model of public EV charging stations • Planning tools for mass deployment of public EV charging stations • Industry-wide codes and requirements for ancillary service (e.g., communication and information processing infrastructure) at public EV charging stations

Next Five Years	Beyond Five Years
• Deployment of on-site renewable energy generators (e.g., roof-top photovoltaic panels and small-scale wind turbines) at public EV charging stations • Development of new parking facilities (e.g., two-way communication capability) for connected and automated vehicles	

Integrated Automated, Connected, and Electric Vehicle Engineering

Next Five Years	Beyond Five Years
• Research on fundamental functional requirements for optimizing the interaction of a growing EV fleet connected frequently to the electric power grid. • Development of small, personal, inexpensive electric vehicles that are highly crash proof • Development of standardized in-vehicle equipment and infrastructure for road use fees based on mileage, location, and time-of-day, needed as fuel tax revenue declines. • Cybersecurity technology • Add connectivity and driver assist automation to EVs.	• Deeper understanding of regional-scale vehicle flow dynamics and electric power demand profiles via math modeling and large-scale simulation to support optimal vehicle mixes and control strategies, especially important if demand for motorized personal mobility rises. • Synergistic combinations of computerized, automated control functions in ACEVs to support minimized energy consumption, range maximization, and reduced collisions. • Accommodation of rising power requirements inside electric vehicles to support connectivity and automation. • Simulation and testing to understand how to ramp up car sharing systems that will optimize the availability of mobility service while minimizing the required fleet sizes. • Automated, driverless refueling of electric vehicles, which makes them more attractive to consumers because of the longer time required for battery charging. • Wireless connectivity for software upgrades and coordination of maintenance requirements. •

Forecasting Market Introduction

This section of the report constructs a roadmap to attaining the vision set forth in the introduction where sustainable road transportation has been achieved through the adoption of automobiles that are automated, connected, and electric. The first portion of this section describes the expert survey and goes on to summarize the survey results with forecasts of increasing levels of automation. It also presents responses to questions on some of the central technology adoption and policy issues that need to be addressed in order to attain this vision. The questions and the responses are self-explanatory and will be presented here with few additional comments. The last portion of this section will summarize the roadmap and some variations of the path to attaining this vision for sustainable transportation.

A panel of twenty experts in the areas of robotics, automotive, and transportation engineering sere recruited and they engaged in a year-long process requiring their response to a sequence of three questionnaires and the anonymous sharing of the survey results with other panelists before responding to next questionnaire. The foundation is a set of forecasts for market introduction of specific systems including freeway automation, automated shuttles, freight platooning, high automation, and full automation. The method involved sequential iteration through the survey process starting with questions related to market introduction and in later stages adding other critical events like public policies required along the way. Upon completing the survey the results were then summarized in a scenario that described the sequence of events as they unfold over the course of thirty years.

Upon completing the standard Delphi survey process and after reviewing the draft scenarios with technical and policy groups the results were then shared with the attendees at the Automated Vehicle Symposium (AVS) held in San Francisco in July and later at the Society of Automotive Engineers (SAE) Convergence Conference in Detroit in October of 2014. The purpose subsequent surveys were to confirm the results represented the insights of the automotive and transportation communities at large. At both of these later events the attendees were presented with the survey questions and original results and asked to provide their own forecasts and priorities. The number of respondents for the AVS questionnaire was 228 with close to 40% with educations in electrical or mechanical engineering, and others in computer science, civil engineering, public policy, human factors, and the social sciences; the number of respondents for the SAE questionnaire was 157 and 85% had backgrounds in electrical or mechanical engineering. For AVS thirty percent identified themselves s experts in automated vehicle systems; nineteen percent identified themselves as experts. The original survey had twenty expert panelists who responded to a sequence of three questionnaires.

This chapter provides a summary of a portion of the results that highlights the roadmap for automated vehicle systems in the broader context of connected and electric vehicles innovations for sustainable transportation. It features the three sets of forecasts from the Graham Institute panel, the AVS attendees, and the SAE attendees and then it explains the scenario that emerged from the Delphi process and the related panel discussions with audiences of public officials and citizens involved in the study. While we decided to prepare a single detailed "most-likely" scenario because of the modest variations in events for the first decade and the low number of events, i.e., full automation, in the latter twenty years, variations in event timing are mentioned in the scenario where they are relevant.

We can start by describing the levels of automation that need to be attained in order to reach this vision ranging from the conventional automobile that relies exclusively on the human driver to monitor the environment and execute control functions including steering, acceleration, and deceleration of the vehicle, to automobiles that rely exclusively on an automated vehicle system that essentially replaces the driver for monitoring and control in all driving modes. These increasing levels of automation are described in detail in SAE's taxonomy and definition of terms related to on road motor vehicle automated driving systems (J3016). The purpose of this document is to facilitate collaboration on automated driving technology and policy development by providing a common taxonomy and definitions and to simplify communications on the topic by establishing common terms of reference. The document also describes increasing levels of automation where the automated vehicle system takes on increasing levels of responsibility for monitoring and control of the vehicle under increasingly complex driving conditions and modes of operation. These levels of automation can be summarized as follows:

- **Level 0, No Automation**: In this level the human driver both monitors the driving environment and executes the conventional control functions including steering, acceleration, and breaking in all modes of operation.
- **Level I, Driver Assistance**: In this level the automated driving system engages to assist the driver in some modes of operation. The automated driving system engages in mode specific execution of steering, acceleration, and breaking using information about the driving environment to assist the driver.
- **Level II, Partial Automation**: Again, in partial automation the human driver monitors the driving environment and the automated driving system engages in mode specific execution to assist the driver in steering and/or acceleration/deceleration using information about the driving environment. The human driver performance all remaining aspects of the driving task.
- **Level III, Conditional Automation**: This level and the remaining levels break from the first three levels in that the automated driving system monitors the driving environment. in conditional automation the automated driving system monitors the driving environment and executes steering, acceleration, and deceleration under specific conditions with the expectation that the human driver will respond appropriately to a request to intervene.
- **Level IV, High Automation**: at this level of automation the automated driving system not only monitors the driving environment and executes steering, acceleration, and deceleration control functions, but it also takes over the fallback performance of the driving task. That is, within the context of the mode of operation the automated driving system is responsible for managing issues and taking over the driving task. The automated driving system performs all of the tasks even if the human driver does not respond appropriately to a request to intervene.
- **Level V, Full Automation**: This level of automation is similar to level IV except that it is extended to all modes of driving. The automated driving system engages in full-time performance of the dynamic driving task under all roadway environmental conditions that have formerly been managed by the human driver.

Since the products in the lower levels of automation have already been introduced to the market the expert panel was asked to address questions related to the market introduction of automated driving systems at level III and above including conditional automation, high automation, and full automation. In this section we will summarize the results of the survey responses describing the specific capabilities of each system and the median predicted date that this capability is introduced to the market along with the interquartile range around the median date.

According to SAE J3016 conditional automation (i.e., Level 3) is part-time or driving mode dependent automation that is initiated and resumed by the human driver during a trip. The automated driving system engages at the request of the driver and disengages under a number of conditions all of which require the human driver to resume the driving task. Therefore when the automated driving system signals an alert the human driver must be prepared to resume the driving task. An example is automated freeway driving where a human driver is required to take over upon alert.

High automation (i.e., Level 4) is a step up from conditional automation where the automated driving system is capable of automatically restoring the vehicle to a minimal risk condition if a human driver fails to respond when alerted. In general the automated driving system will alert a human driver several seconds before the driver needs to intervene. If the human driver does not respond to the alert then the automated driving systems restores the vehicle to minimum risk conditions. Examples of high automation include freeway driving, campus shuttle, and valet parking.

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The real-time systems design and engineering challenges for restoring the automated driving system and the vehicle minimal risk conditions are significant and depend on vehicle maneuvers as well as the roadway and traffic environments. Not only must the vehicle fail safely and cause no harm but it must also fail to an operational state and bring the vehicle and passengers to safe harbor. For example, automated freeway systems at the conditional automation level may need to bring the vehicle with a system failure safety to rest on the shoulder of the road. If automotive adopts the approach of avionics this will require system and component redundancies where faults are indicated by differences and each system can back up the other. This type of redundancy will also add to vehicle cost as well as possible public infrastructure cost.

Full automation (i.e., Level 5) is the next step and highest form of automation where the automated driving system performs all aspects of the dynamic driving task under all roadway and environmental conditions that are normally managed by a human driver. Again, this includes bringing the vehicle to a minimal risk state in the event of a critical system failure or emergency event. The robotic taxi is an example where when given a destination the taxi is capable of performing the entire driving task on public roadways.

Freeway automation engages and disengages the automated driving system on the freeway at the driver's request much like a cruise control system. While the system is designed to travel from entrance to exit at the request of the driver in normal traffic it will not engage or alert the driver of disengagement in case of unusual traffic or weather events or in the case a system fault has been detected. In a Level 3 or Conditional automated driving system the driver will be alerted to take over and bring the vehicle to a minimal risk condition. In the case of a Level 4 or High automated driving system the driver will be alerted but the vehicle can bring itself to a minimal risk condition. Along the freeway the minimal risk condition may be driving to a stop along the shoulder of the road or driving to an exit ramp or driving to a designated safe harbor location.

Automated freight platooning enables trucks to actively travel together with other equipped vehicles and coordinate in tight formation like a train of electronically connected trucks on the highway. While there are many variations on the design and functionality of platooning systems with some relying more on the communication between two of more vehicles and others relying more on coordination through the infrastructure, the questionnaire did not specify the technology. Rather, the questionnaire specified the functionality of cooperative adaptive cruise control and automated steering to coordinate vehicles and shorten headways and reduce wind resistance. In this case there are drivers in all trucks and platooning does not require a dedicated freeway lane. Outside of the platoon the driver operates the vehicle with possible assistance from lower levels of automation. This is a SAE Level 4 application that will alert the driver if automated driving cannot be maintained and can maneuver to bring the truck to a minimal risk condition. While the fail operational and safe harbor states were not described this may involve bringing the entire platoon to a safe stop or the exit of one or more vehicles from the platoon.

The automated shuttle is a Level 4 or fully automated application that travels at low speeds within a closed or gated campus placing some limits on the vehicle and pedestrian traffic in that environment. These vehicles generally operate at speeds below 20 miles per hour and in some cases may travel along separate paths dedicated exclusively to shuttle use and in other cases travel on roadways or other surfaces with mixed vehicle and pedestrian traffic. For example Google recently began experimenting at National Aeronautics and Space Administration's (NASA's) Ames Research Center with a two-seat prototype with no steering wheel or other controls other than a stop-and-start button. Similarly the United States Army Tank Automotive Research, Development and Engineering Center (TARDEC) is planning a shuttle system for Fort Bragg to help transport wounded warriors from their barracks to to the Army Medical Center and back. These systems generally do all the driving including 360 environmental sensing and the execution of steering, acceleration, and braking as well as maneuvering to bring the vehicle to a minimal risk condition for the passengers as well as pedestrians and other vehicles on the campus.

High automation in the context of the questionnaire was a Level 4 part-time or geographically restricted driving system that could perform all aspects of the dynamic driving task on some surface streets as well as highways in these environments. This is an extension of the automated freeway system that adds urban and rural environments under the right conditions. As with the other Level 4 systems the automated driving system monitors the environment and executes steering, acceleration, and braking as well as alert the driver to re-engage when necessary and has the ability to bring the vehicle to a minimal risk condition if the driver cannot engage. The human driver is ultimately responsible for driving the vehicle outside these restricted environments and providing intended destinations on roads supporting automated driving.

Full automation will control the vehicle from beginning to end of trip, both on highway and surface streets, urban and rural, without human intervention. The automated driving system monitors the environment and actuates steering, acceleration, braking, and other functions for driving the vehicle. These types of systems may take on the role an autonomous chauffeur in a robotic taxi that picks up riders and drops them off before moving autonomously to the next rider or parking/charging space. The vehicle is designed to fail safely and return the vehicle to a minimal risk condition if a problem occurs. This is the fully automated form of transportation that has captured the imagination of the general public as promoted by Google and promises to offer a feasible alternative for the mobility disabled as well as autonomous package deliveries and other solutions that are independent of a human driver.

Note that in the diagram below and all of the remaining figures we've identified two sets of numbers for the predicted market introduction at the first quartile, median, and third quartile of the distribution of responses. The numbers on the top level in the figure, the top row, are those of our expert panel and are the final results after three iterations through the survey process. We had 20 expert panelists who participated in all three rounds of the expert survey. Three of the original 23 panelists dropped out due to schedule conflicts in the firs round of the study. The second, or bottom set of numbers in the table are those of the conference attendees at the Transportation Research Board (TRB) and Association of Unmanned Vehicle Systems International (AUVSI) Automated Vehicle Symposium in San Francisco, scheduled from July 14 through July 17 in 2014. Then in mid October we conducted one last round of the survey with attendees from the Society of Automotive Engineers Convergence Conference 2014. We provided the same set of questions to the conference attendees along with the resulting median responses from our panel of experts. The purpose of last two surveys was to serve his outreach to the broader community and to check our results with an extended set professionals who were also familiar with if not experts on this subject matter. There were 217 attendees at the Automated Vehicle Symposium who responded out of a total of around 560 attendees at the event. We had 157 respondents from the SAE Convergence Conference in Detroit.

The first two rounds of the original expert panel survey made extensive reference to the NHTSA levels of automation. However, many of the questions were reformulated to enable a transition to the SAE definitions and levels of automation in the last round of the Delphi expert panel and the two automotive events; AVS and Convergence. Throughout the discussion of the results we use the SAE levels and definitions of automation unless otherwise noted in the title of the section. Discussions about the NHTSA levels are indicated in the section titles. We will start by addressing the lower level of automation starting at NHTSA Level I, III and level IV and then move up to the higher levels include vehicles with high automation and full automation.

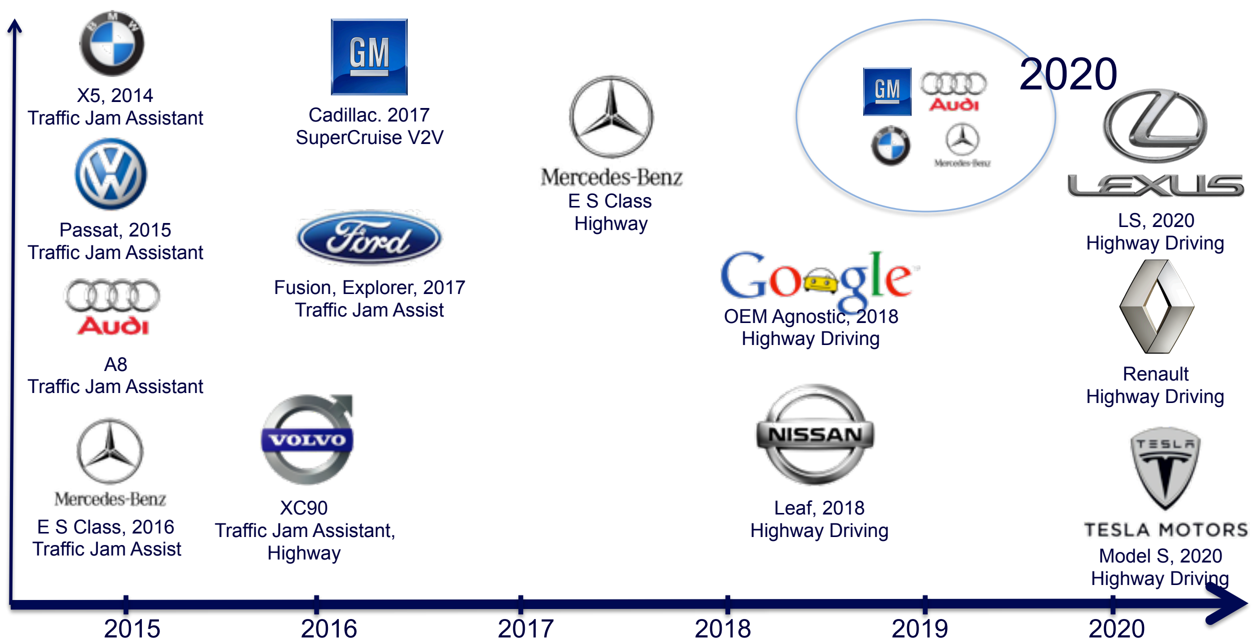

Figure 21. Announcements of Plans for Introducing Automation

Partial or Combined Function Automation (NHTSA Level 2)

This part of the survey was designed to specifically deal with Level 2 vehicle automation, as define by NHTSA. While the table below presents the opinions of panelists regarding the timeline of events and their perspective whether or not these applications should be mandates, below is a summary of their comments as it relates to Level 2 automation:

1) Anything that requires testing between multiple OEMs will require projects by government to ensure seamless roll out into the general public.
2) The features listed in the table seem to be more convenience (driver assist) features and not active safety. Therefore, it is not expected from the government to require these features on future vehicles. However, forward collision warning/assist and pedestrian detection warning/assist (not listed here) could be required by the US government. Also, government should only get involved in these with pilot programs to help increase the technology acceptance and increase deployment. However, in most cases related to this technology, the market is already ahead of the US Government.

> **Round 2; Question 2:** Combined Function Automation (Level 2) In light of the results from round 1 of this survey shown below, please answer the following question:
> - Select the year that automakers will begin including the Combined Function Automation (Level 2) features listed below in passenger vehicles in the United States.
> - Will this feature eventually be mandated on all new vehicles in the United States?
> - Should there be a United States government-funded pilot project for this feature?

Table 4. Expert Forecast of Level 2 (Combined) Automation Features

Level 2 Automation Feature	Year (Median)	Interquartile Range		Mandated		Government Funded Project	
		25%	75%	Yes	No	Yes	No
Traffic Jam Assist for low-speed applications	2015	2014	2016	19%	81%	24%	76%
Integrated Lane Centering and Adaptive Cruise Control (ACC) for high-speed applications	2014.5	2013	2017	29%	71%	29%	71%

The Delphi survey method uses statistical summaries of numerical forecasts to measure and promote consensus among the panel of experts. Levels of consensus in the forecast dates for the expert panel selected for the Graham institute study are indicated by the range of variation in the forecast dates provided by the respondents for each of the automated systems under consideration. So, for example, the interquartile range, that is the measured distance between the first quartile and the third quartile, is two years for both SAE Level 3 freeway driving and SAE Level 4 automated shuttle, while it is ten years for the forecasts on full automation. Lower levels of variation, for example for market introduction dates for shuttles and for freeway driving, indicated higher levels of panel consensus, than for the higher levels of variation in the market introduction forecasts for full automation. The quartiles are also another measure for levels of optimism or pessimism in the forecasts. That is, the first quartile, or possibly more optimistic technology forecast date, has 25% of the panelists at or below the measure and 75% at or above the measure.   Similarly, the third quartile, or possibly more pessimistic technology forecast, has 75% at or below the measure and 25% at of above.

Table 5. Expert Panel and Survey Forecast for Market Introduction of Automated Driving Systems SAE Levels 3, 4, and 5

Automated System	SAE Level	Fail Safe Fallback	Survey	Years at the Quartiles		
				1st Quartile	2nd, Median	3rd Quartile
Freeway	3	Driver	Graham	2017	2018	2019
			TRB/AUVSI	2018	2019	2020
			SAE	2018	2020	2021
Freeway	4	System	Graham	2018	2019	2022
			TRB/AUVSI	2018	2020	2024
			SAE	2019	2020	2023
Freight Platooning	4	System	Graham	2019	2020	2022
			TRB/AUVSI	2019	2020	2024
			SAE	2019	2020	2024
Shuttle	4	System	Graham	2015	2016	2017
			TRB/AUVSI	2016	2018	2020
			SAE	2017	2018	2020
High (freeway & urban)	4	System	Graham	2024	2025	2030
			TRB/AUVSI	2024	2025	2030
			SAE	2024	2025	2030
Full	5	System	Graham	2025	2030	2035
			TRB/AUVSI	2027	2030	2035
			SAE	2028	2030	2035

Another way to summarize the results is to look at the third quartile or more pessimistic forecasts. From this perspective the automated shuttle systems will be introduced in 2017, automated freeway in 2019, freight platooning in 2022, high automation in 2030, and full automation in 2035. It is clear that in either case, whether from the more optimistic perspective or from the more pessimistic point of view that the panelists expect the early forms of conditional and high automation on highways or in closed communities to be introduced within the next seven years. However, when it comes to automated vehicles traveling in mixed traffic in cities the panelists expect introduction in the range of from ten to twenty years.

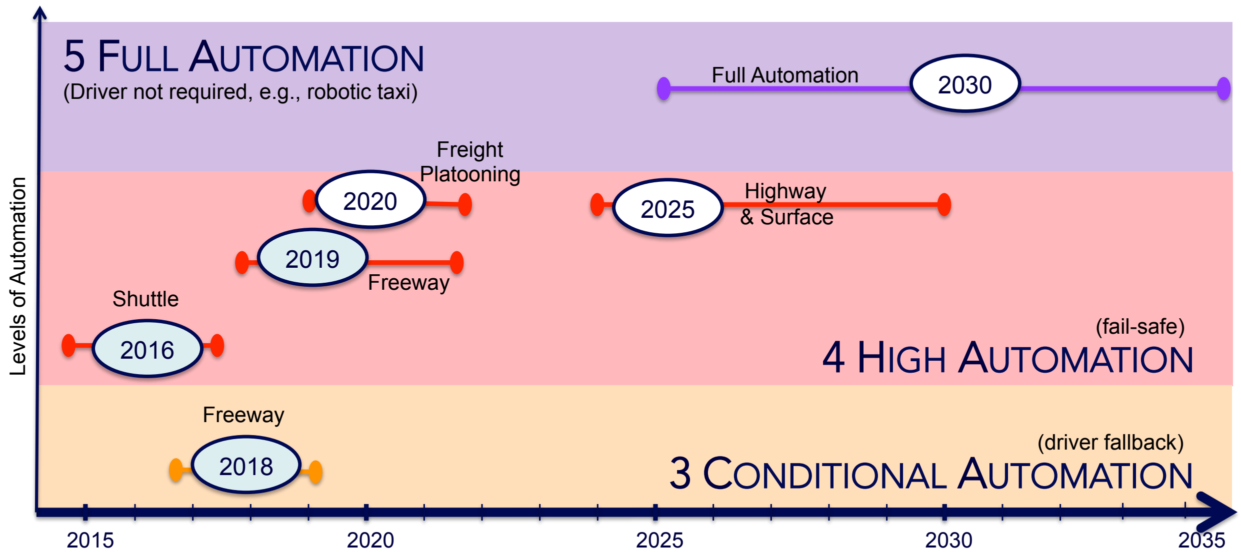

Figure 22. Graham Institute Expert Forecast Summary Measures Median and Interquartile Ranges

Figure 22 plots the Graham Institute panel's median forecast for each of the automated systems and shows the interquartile range on the bars behind the dates. So, for example, the median forecast date for the automated shuttle systems is 2016 and the interquartile range is two years from 2015 to 2017. This shows a relatively high degree of consensus for the near term, i.e., 2016, market introduction of the automated shuttle. By contrast, there is much less consensus on the market introduction of full automation with a median forecast of 2030 and an interquartile range of ten years between 2025 and 2035. In fact, there was very little agreement among the panelists for the market introduction of full automation. One panelist forecasted as early as 2019 and another panelist forecasted it would never be introduced to the market. However, it is interesting to note that over the course of the three rounds of the survey the number of "never" forecasts for all the of the levels from 9 in the first round to 1 in the third round. This and the generally lower interquartile ranges over the course of the three rounds indicates a growing confidence in the overall technical feasibility, consumer acceptance, and institutional support for all of the levels of automation.

In addition to the forecasts on market introduction the respondents also answered a variety of questions related to other key events and challenges. Many of these responses are the sources for the comments in the scenario below. The full responses are provided in the final report from the Graham Institute for Sustainability (Underwood, 2014a, 2014b). However, some of the most relevant responses can be summarized quickly in a few sentences. First, we asked the Graham panelists to rank the difficulty of overcoming barriers in fielding SAE Level 5 fully automated vehicles in all environments, with 1 being the most difficult barrier and 5 the least. They responded as follows: technology (4.88 mean), legal liability (4.33), regulations (4.27), cost (3.47), roadway/infrastructure (3.08), consumer acceptance (2.47), and social acceptance (2.33). Interestingly the TRB ranking had a similar sequencing only technology was pushed down to the 4th position and legal liability came to the top. The SAE ranking was nearly identical with technology at the bottom of the list. One could speculate that this is a function of the respondents' technical expertise in the subject because of the strong correlation.

Automated Shuttle for Pedestrian Zones

An automated shuttle is a vehicle that travels with low speed over short distances in a fully automated mode. These small lightweight vehicles are likely to be found in closed campuses or in areas like pedestrian malls, university campuses, medical centers, airports, or other areas where high-speed automobile traffic is off limits. They may be electric powered and handle like a golf cart. These systems will often have a top speed of 15 to 25 mph and will move even more slowly in pedestrian or other shuttle vehicle traffic. These can be thought of as very defensive vehicles that would have audio alerts for nearby pedestrians or other vehicles. An operator may be present to assist the passengers and to help you in a situation's. However the vehicle will be designed to fail safely if any kind of problem occurs.

Figure 23. Navia Induct Automated Shuttle, Multiple Passenger Vehicles

While an automated shuttle monitors the environment, controls the vehicle, and provides failsafe backup capabilities it is also designed to operate in an environment where there is little or no risk of crashing into other larger and faster vehicles. This simplifies the operating environment and makes it easier to perform maneuvers than in a high-speed environment with other larger vehicles.

Our expert panel provided a predicted market introduction of the year 2016 with an interquartile range from 2015 to year 2017. According to our panel this was the first type of system to be introduced to the market of all the automated systems addressed in our survey. We asked the same question to attendees at the symposium and provided the median interquartile range from our expert panel. Attendees at the symposium provided forecasts on the whole somewhat further out into the future with a median of the year 2018 and a interquartile range from the year 2016 to year 2020. Nevertheless, in both sets of forecasts the expectation is that automated shuttles are going to be one of the earliest forms of automated vehicles to be introduced to the market.

Figure 24. Google Shuttle Vehicle

The Google shuttle vehicle in Figure 24 has no traditional hood or engine compartment and no controls apart from the start and stop button. It is electrically propelled and travels at a maximum speed of about 25 miles per hour. The front of the vehicle is made of a foam like material in case it hits pedestrians.

Automated Freight Platooning

For automated freight platooning at level IV the panel was asked to provide their predicted date of our market introduction for a system that had cooperative adaptive cruise control and automated steering where short headways would reduce wind resistance and there would be drivers in all the trucks. In this case they were asked to assume the drivers will be required to respond to a request intervene in case of a problem. We didn't specify whether this would be in a dedicated lane however the vehicle in this case was designed to fail safely if the driver did not respond.

Figure 25. Automated Freight Platooning, NEDO, Japan

The median response for our panel of experts for market introduction of the automated freight platooning system is the year 2020 with an interquartile range from 2019 to 2022, or a range of three years. This is a very tight distribution of responses suggesting a high level of agreement on the year 2020 among our panel of experts. The attendees at the symposium were provided with this median of 2020 and the range from 2019 to 2022 and were asked to provide their own forecast date for market introduction. The attendees from the symposium had a distribution with an identical medium of the year 2020 and they also had a very tight distribution from the year 2019 to the year 2024. The expert panelists in the symposium attendees had very similar responses on the predicted date for market introduction of automated freight platooning with the attendees of this symposium with the distribution waited further into the future will with a third quartile of 2024.

Automated Freeway Driving

We asked our expert panel to address two types of automated freeway driving. In the first case the vehicle travels on the highway from entrance to exit without any driver assistance. The driver can engage or disengage his capability but they do today with the cruise control system. Like cruise control of today if the automated freeway driving system disengages the driver is expected to take over control of the vehicle. Our expert panel expects this to be one of the first systems to be introduced to the market with a median response of the year 2018 and an interquartile range from 2027 to 2019. The attendees at the symposium were provided with the same question along with the responses from the expert panel in their median response date was 2019 or one year later with an interquartile range from 2018 to the year 2020. So, again the overall distribution of responses of both the expert panel and the conference attendees were very similar with the different on here, that is 2018 versus 2019, in the median respon

Fail Safe Automated Freeway Driving

We also ask our expert panel to address the year of introduction for a similar automated freeway driving system where, again, the vehicle can travel on the highway from the entrance to the exit without direct assistance from the driver. Again, the system is very similar to automated cruise control when the driver will engage or disengage this capability. However this system is different in that should the automated driving system not be able to handle the road conditions or the driving situation the system will pull into failsafe mode and take appropriate actions without driver intervention. The system does not rely on the driver while it is in this mode. However, the system may make a request for the driver to intervene before it takes a failsafe action. If the driver does not respond the system will taken appropriate action which may mean the vehicle pulls off the side of the road.

For the automated freeway driving system with failsafe capabilities our panel of experts responses had a median of the year 2019 with an interquartile range from 2018 to 2022. The attendees at the symposium had a very similar distribution of responses with a median year of 2020 and an interquartile range from 2018 to 2024. Again, the distribution of responses for the attendees at the symposium were distributed further out in time.

High Automation: Freeways and Surface Streets

The next level it was addressed by our panel is the SAE level IV described as high automation where, in this case, the vehicle is in control from the beginning to the end of the trip, both on highway and on surface streets, urban and rural, and where the driver can respond to request from the system to intervene. However, if the driver does not respond the vehicle designed to maintain control and to fail safely. This is the type of system where there is a human operator in the drivers seat, but this human operator can engage in other tasks without concern for monitoring the environment or needing to take over control for their own safety.

Our expert panel response had a median of the year 2025 with an interquartile range from 2024 to 2028. This range is still very tight and suggests that there is significant agreement on the date of introduction for a high automation system. Interestingly, the question and the median dates the symposium attendees also responded with a median of 2025 and a similar range of 2024 two 2030. From the perspective of the Delphi procedure this would suggest a relatively high level of consensus on the year 2025 for the introduction to the market of vehicles with high automation.

Full Automation: Autonomous Chauffeur

In full automation a self-driving vehicle is a control from the beginning to end of the trip, both on Highway and surface streets, urban and rural, without assistance from a human driver. One could envision a self driving taxi that could take itself from one location to another without a human onboard. Our panel responses for full automation at a median of the year 2030 with a wide distribution described in the interquartile range from 2025 to 2035 suggesting there was little consensus on a specific date. The responses of the conference attendees were very similar with the median of 2030 and a range from 2027 to 2035. So, the distribution of responses between our expert panel in the conference attendees was very similar, yet, they were similar only to reflect little agreement on a specific date for the introduction of full automation.

So, if we accept the median response from our expert panel as the date for system introduction on our roadmap to full automation then one could make the case that in 16 years, that is, in the year 2030 a fully automated vehicle system will be introduced to the market. In other words, there will be commercial purchases a fully functional self-driving vehicle that could essentially serve as a taxi without a driver. This suggests that a lot of progress will be made in the next 16 years. However, an alternative approach for interpreting the forecast is that because there is very little agreement or consensus on when full automation will be introduced to the market it is therefore quite difficult to predict when this will happen. Yet, another interpretation of these results might draw on the higher level of panel agreement on the introduction of conditional and high automation systems, and assuming these can be accomplished within the next decade then look more carefully at the influencing factors and what they might suggest needs to be accomplished in order to introduce vehicles with full automation. We will attempt to take the later approach and assess what can be draws from these predictions.

The next figure summarizes all of the forecasted dates for market introduction of automated vehicles ranging from conditional freeway automation all the way up to full automation. According to our panel of experts the first system to be introduced to the market is the automated shuttle. The automated shuttle is introduced in 2016. While the automated shuttle has a capability defined as high automation that includes monitoring, vehicle control, and failsafe backup operation, it is also a system that is operating in an environment at low speeds and with few objects in the environment like other vehicles traveling at high speed and posing risks of damage. Again, these vehicles are known for defensive driving and can provide warnings to pedestrians and come to a complete stop very quickly if necessary. Nevertheless, these systems will provide a laboratory for identifying and classifying objects and learning successful maneuvers that will assist in the design of future high-speed on road systems.

Following the sequence of deployment the next system to be introduced to the market according to the median forecasts of our panel is the automated freeway system that operates very much like adaptive cruise control only it also keeps the vehicle within the lane allowing the driver to remove his or her hands from the steering wheel. Also, as mentioned earlier, my cruise control the system requires the driver to be engaged and to monitor the environment at all times. The driver may also be required to take over control of the vehicle events where the automatic control because precarious. As described in the preceding section it also relies on the driver to take over and backup situations. These systems are somewhat controversial because of the challenging human factors issues associated with disengaging and re-engaging the driver. Nevertheless, our expert panel provided a median forecast of 2018 for the introduction of this automated freeway system. However, it should not be too much of a surprise that the related automated freeway system at level IV has a median forecast of 2019, one year after the introduction of the conditional automated system.

Both the automated shuttle and the automated freeway systems were identified as early to market systems primarily because of their limited access environments for operation. The shuttles operate primarily in pedestrian zones that are closed to automobiles. The limited access highway systems for freeway automation have traffic traveling in a single direction without intersections or pedestrian traffic.

The automated freeway system and the level for category have an automated driving system that will fail-safe in cases of emergency. The failsafe strategy for these vehicles was not discussed in any detail in the panelist responses, however, should the driver not be able to respond and take over control of the vehicle the failsafe system would kick in and most likely bring the car to a safe stop at an appropriate location along the freeway. This would suggest that there may be some need for infrastructure planning to enable the automated failsafe capability. For that matter, is probably desirable to have safe alternatives along the roadway for human drivers too.

Freight platooning is the next system to be introduced according to the median forecast of the year 2020. Like the preceding systems the interquartile range of responses is relatively small reflecting a high level of agreement among the panelists. The platooning and trucks like the other earlier systems are under development at this time and being tested at various sites in Europe, Japan, and the United States. The primary business justification for the platooning system is increased fuel economy due to decreased wind resistance and drag for the following vehicles. These systems are very similar incapability to the automated freeway systems with combining highly controlled adaptive cruise control and possibly lane keeping. However lane keeping is not essential. These systems are designed to maintain short headways between the vehicles to manage the wind resistance and increase fuel economy. These systems are identified as level IV because we asked to panelists to consider only systems that designed to be fail-safe.

Road Environment	Speed	Road Surface	Road Access	Vehicle Traffic	Pedestrians	Objects	Signage & Signals
Highway	Very High	Even Marked	Limited	One Way Merging	Rare	Violations	Common
Country Road	High	Mixed, Parking	Open	Two Ways Intersections	Low Frequency	Remote Events	Common. Signals
Urban	Medium	Mixed, Parking	Open	Two Ways Intersections	Common Event	Pets & Other Events	Common, Signals
Pedestrian Zone	Low	Mixed	Limited	Pedestrians Slow Vehicles	Predominant Event	Pets and Other Event	Occasional
Off-Road	Low	Limited	Limited	Limited Unstructured	Low Frequency	Great Frequency & Diversity	Uncommon

Figure 26. Road Environments and Features
Considered in Design of Automated Vehicle Systems

The high automation system reflects both the leap in technology and, according to our expert panelists, a leap in time. Our panelists had a median prediction of 2025 for vehicles that can monitor the environment and control the vehicle from beginning to end of the trip both on a highway and surface streets in both urban and rural settings. These systems will most likely be designed to request a driver to intervene in places where the automated system perceives situation where the vehicle is difficult to control. For example, one could imagine the vehicle not enabling high automation in certain weather conditions or requesting the driver to takeover in these conditions. However, under normal conditions the vehicle should be able to monitor said the situation and control the vehicle from beginning to end. The vehicle is also designed to fail safely.

The environment for high automation is much more demanding of the automated driving system in terms of maneuvers for lane changes, at intersections, assisting with parking, detecting and avoiding other vehicles, pedestrians and pets and other objects, managing both signed, unsigned, and signalized intersections, managing to a traffic, managing roundabouts, and the list can go on. The road and traffic environment on surface streets in urban and rural areas is very challenging.

The last in the sequence is full automation and our panel provided a wide range of forecasted dates for this capability that is totally independent of a human driver. The automated chauffeur or taxi had a median forecast of 2030. But the interquartile range started at 2027 and ended at 2035 and this means that a quarter of the responses, or at least five of the respondents, forecast of the system to be introduced to the market beyond 2035. It is interesting to note that all of the panelists provided a date for introduction of full automation; none of them provided the “ never "response which was an option.

The next chart is similar to the previous one showing median forecasts for all the systems and categorized by the SAE levels. The difference is that this chart summarizes the responses of the attendees at the Automated

Vehicle Symposium that was held in San Francisco in July, 2014. As described above the median forecasts are very similar to the median forecasts of the expert panel for the study. Where the median forecast for the automated shuttle among expert panelists was 2016, the conference attendees had a median forecast of 2018. Where the median forecast of the expert panel for freeway automation was 2018 for systems where the driver is the backup and 2019 where the automated driving system is designed to be failsafe, the median forecasts of the attendees was 2019 and 2020 respectively. Also note that the interquartile ranges for most of the projections were larger for the conference attendees than for the expert panel. The reader should also be aware that the attendees at the symposium were provided with the forecasts of our expert panel. Nevertheless, the forecasts are very similar with the automated shuttle being the system that is first introduced to the market, followed by freeway automation, then freight platooning, high automation, and finally full automation. The medians for freight platooning, high automation, and full automation are identical.

The questionnaire provided to the attended of the symposium had several additional questions addressing automated valet parking, truck platooning without drivers in the following vehicles, and an automated taxi that would take a child to school. we are not going to provide a detailed analysis of these responses in this report. However the distribution of the responses to all the systems from the survey of attendees is provided in the last chart. There were a total of 216 responses and both the distribution of responses and the median response for each one of the systems is provided in this chart. Note that the questions about the forecasted date for each system or separate from the questions on the time periods provided at the bottom of the chart. So, there may be some inconsistency between the distribution of responses the questions about the periods and the median responses that addressed the dates directly. However, this is difficult to discern for certain because most of the median responses were provided at the breakpoint between the time periods. For example, for the failsafe freeway driving the median date is 2020 and it is located exactly at the breakpoint between “before 2020” and “2020 through 2024.” Nevertheless, this chart provides a quick summary of all the responses to all the systems addressed in the survey.

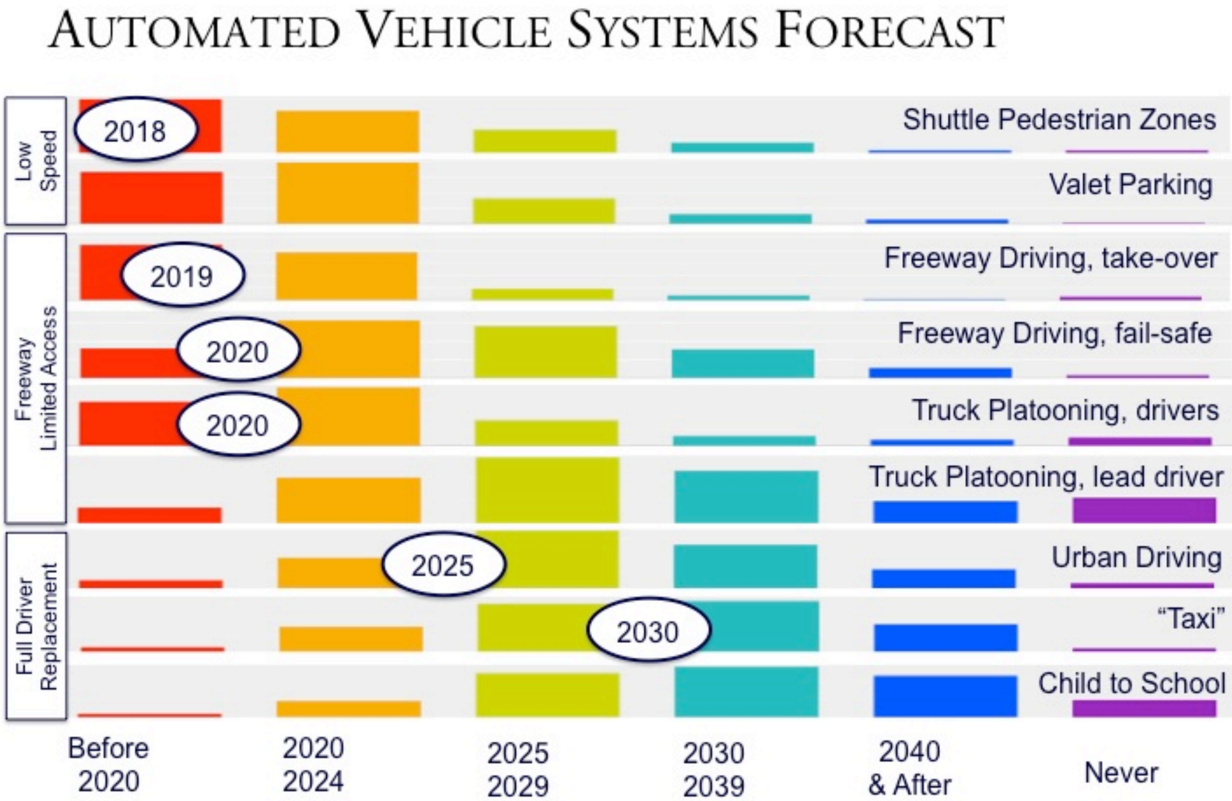

Figure 27. Automated Vehicle System Forecast Summary

Round 2; Question 1: The list below represents a set of possible automated vehicle technology milestones that will be accomplished by the automotive industry in the United States. Please select the year that this milestone will be accomplished in the United States. For items in this list that believe should be removed or will never occur please indicate with "never" response options. Will government mandate the systems on all new vehicles? Will the government support a pilot project on this type of system?

Table 6. Expert Forecast of Additional Automated Vehicle Milestones

Milestones Market Introduction	Median	Interquartile Range		Never
OEM's introduce passenger vehicles with some automated capabilities that include tight vehicle platooning (less than a half second gap between vehicles).	2020	2020	2022	1
OEM's introduce vehicles with some automated capability to market that include effective navigation and localization solutions for GPS denied areas (e.g., urban canyons, parking structures, etc.).	2018	2017	2020	2
OEM's introduce vehicles with some automated capability to market that use accurate 3d digital map-matching to supplement vehicle navigation and localization	2018	2016	2020	1
Companies introduce communication infrastructure (e.g., DSRC, Cellular, etc.) that is able to handle timely transfer of certified 3d digital maps to vehicles with some automated capability	2018	2017	2019	
OEM's introduce vehicles with some automated capability to market that are integrated with both infrastructure and other passenger vehicles	2019	2017	2020	

Limited Self-Driving Automation Milestones (NHTSA Level 3)

Round 2; Question 4: In light of the results from round 1 of this survey shown below, please answer the following question:

- Select the year that automakers will begin including the Limited Self-Driving Automation (Level 3) capabilities listed below in passenger vehicles in the United States.
- Will these capabilities eventually be mandated on all new vehicles in the United States?
- Select the year that vehicles with these capabilities will reach their maximum market share of all new vehicles sold in the United States.
- Select the maximum market share percentage that vehicles with these capabilities will achieve in the United States at the year you selected in part (3) of this question.
- Should there be a United States government-funded pilot project for this capability?

Table 7. Expert Forecast of Urban and Rural Automation

Passenger Vehicle market introduction	Median	Interquartile Range		Mandated	Maximum Market Share	Government Pilot
Level 3 Urban	2024	2022	2025	3 yes 17 no	50% 2035	10 yes 10 no
Level 3 Rural	2023	2020	2025	4 yes 15 no	50% 2035	6 yes 13 no

Full Self-Driving Automation Milestones (NHTSA Level 4)

Assuming that a level 4 automated vehicle could operate safer than humans, panelists were asked if it would be possible to have these vehicles on public roads without a driver (or passenger) present in the vehicle. Again, all the respondents unanimously said that it will be possible to have such vehicles operating on public roads without a driver or passenger in the vehicle. Their agreement with the statement above was highly contingent upon reaching a point where the technology, infrastructure, etc. are made available and the vehicles are proven to be safer in any and all conditions (snow, ice, wind, urban, highway, rural, etc). Also, another point that could be seen in the comments was ensuring pedestrians and driver's know a robot is in charge and activated and all details are recorded in case there is any kind of accident However, there could be a progression path towards such vision. The said situation could be first initiated or at least experimented with in parking lots (low speed operation) and for disabled/aged people who cannot walk to the vehicle but this should be short distance, low speed situations (such as shared vehicles in city center).

Round 2; Question 5: In light of the results from round 1 of this survey shown below, please answer the following question:

- Select the year that automakers will begin selling Full Self-Driving Automation (Level 4) vehicles in passenger vehicles in the United States.
- Will this capability eventually be mandated on all new vehicles in the United States?
- Select the year that vehicles with these capabilities will reach their maximum market share of all new vehicles sold in the United States.

- Select the maximum market share percentage that vehicles with this capability will achieve in the United States at the year you selected in part (3) of this question.
- Should there be a United States Government-funded pilot project for this capability?

Table 8. Expert Forecast of Level 4 Automation Features

Milestones market introduction	Median	Interquartile Range		Never	Mandated	Max Market Share	Date Max Market
Level 4, driver in control loop	2025	2025	2028	1	4 yes 16 no	70%	2040
Level 4, driver outside the control loop	2032	2025	2040	0	4 yes 16 no	70%	2045

Market Milestones (NHTSA Level 4)

It is believed that advances in the automated vehicle technology will be driven be some market milestones. Panelists were presented with a list of such milestones and asked to express their opinion regarding the timeline related to each of these milestones and provide additional comments if they believe there are other milestones that were not captured in this table. Below, you can find the results gathered from the responses provided by the panelists.

Round 2; Question 8: Please specify the years that the following milestones will take place.

Table 9. Expert Forecast of Additional Policy Milestones

Milestones market introduction	Median	Interquartile Range		Never
New OEM introduces first level 4 vehicle	2025	2019	2028	2
First insurance company discounts insurance for level 4 vehicles	2025	2020	2027	
First OEM launches a redesigned purpose built level 4 vehicle (e.g., smaller)	2024	2020	2025	
50% of passenger vehicles are fully drive-by-wire across all major control functions	2023	2020	2025	

1) City zone designated level 4 only.
2) First automated vehicle parking lot/structure introduced in 2018 timeframe.
3) DSRC implementation and other "sensor-friendly" (more S/N) infrastructure features will be important as well.

The Road Ahead: Automated, Connected, and Electric

This section summarizes and integrates the results from the earlier sections addressing automated, connected, electric vehicle systems. We address the evolution of the systems over a timeframe of 30 years. We start with a high level framework we laid out in the first section of the report and add the expert panel forecasts for introducing the automated and connected vehicle systems to the market and the related policy and technology milestones. We also tie the developments in automation to an existing roadmap for electric and hybrid vehicle developments. We summarize the final roadmap for all the systems in a sequence of scenarios that include automated, connected, and electric vehicle milestones.

The next set of figures summarizes the expert panel forecasts for the introduction to the market of the various levels of automation and specific systems that were addressed in the survey. The first figure presents the median forecast of the panel for each of the systems including lane keeping integrated with adaptive cruise control, traffic jam assist, conditional freeway automation, automated shuttle in a pedestrian zone, failsafe freeway automation, freight platooning, high automation and urban environment, and full automation.

The chart also shows the markets for freeway automation and urban automation increasing over a period of 10 years the maximum level specified by the panel. For freeway automation the panel had a median maximum level of penetration of 50%. For urban automation the panel had a median maximum level of penetration of 70%. The median panel forecast for partial automation and driver assist was 50%.

The figure shows the median forecasts for each of the systems starting with traffic jam assist and integrated late keeping an adaptive cruise control in 2014. It then moves on to the higher levels of automation including conditional where the median for freeway automation is 2018. Then moving up to high automation, for example, fail-safe freeway automation, this more advanced form is introduced in 2019. Before that the automated shuttle is introduced in 2016, freight platooning is introduced in 2020, urban self driving is introduced in 2025, and the fully automated self driving taxi vehicle is introduced in 2030. These all reflect the median estimates from the panel of experts.

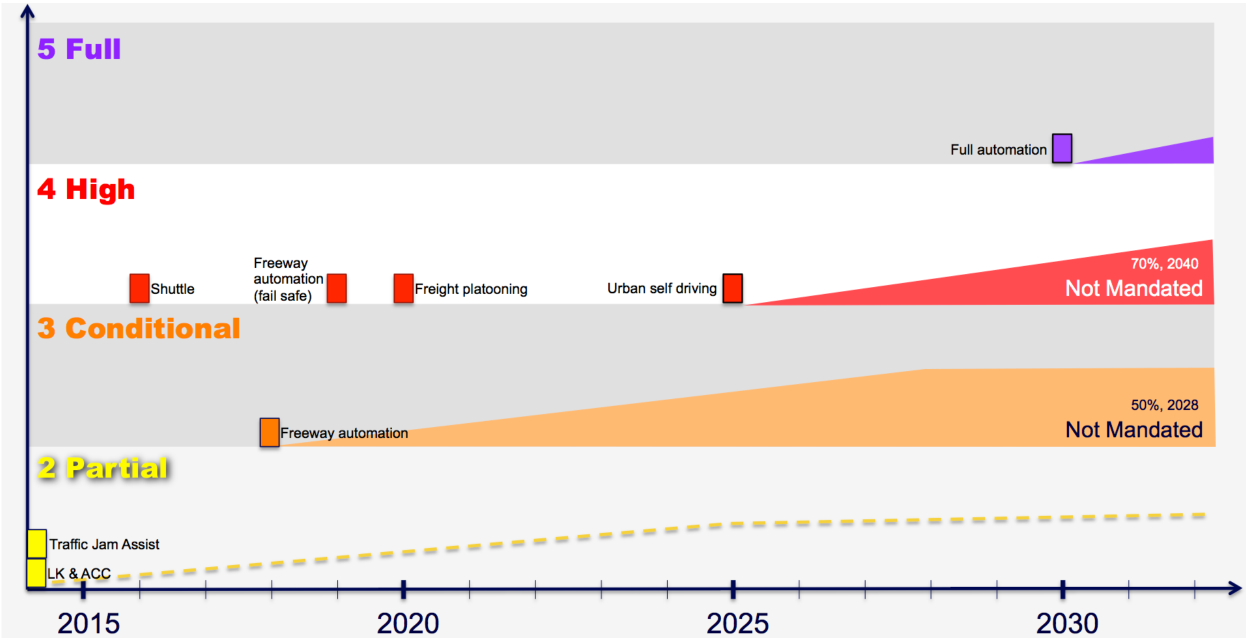

Figure 28. Expert Panel Median Market Introduction Forecasts

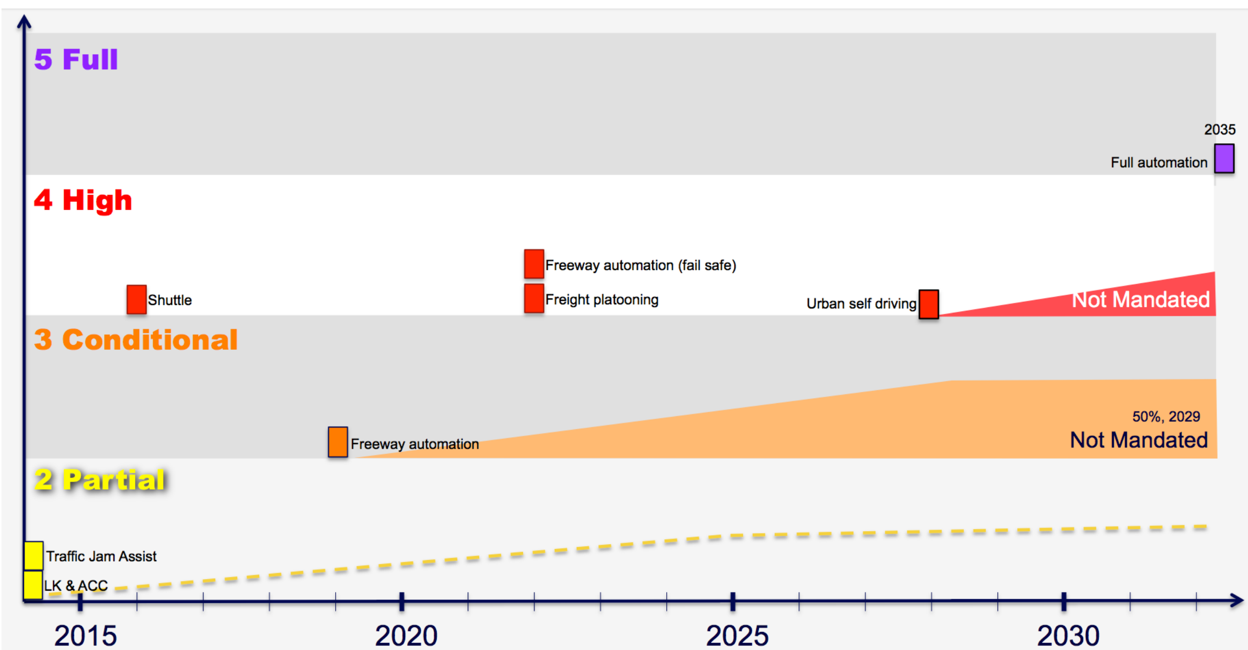

Figure 29. Third Quartile Market Introduction Forecasts, "Pessimistic"

The next figure summarizes the expert panels third quartile estimates for each of the systems they assessed. The purpose for exploring the third quartile is to assess the panel's responses with less optimistic or possibly a pessimistic measure of the forecasted date for introducing each of these systems to the market. What we find in the third quartile shows little variance from the median estimates. Freeway automation is perhaps most affected by this third quartile assessment with the introduction of conditional freeway automation in 2019 in the introduction of failsafe freeway automation in 2022. Urban self driving slides back to 2028 and full automation was back to 2035.

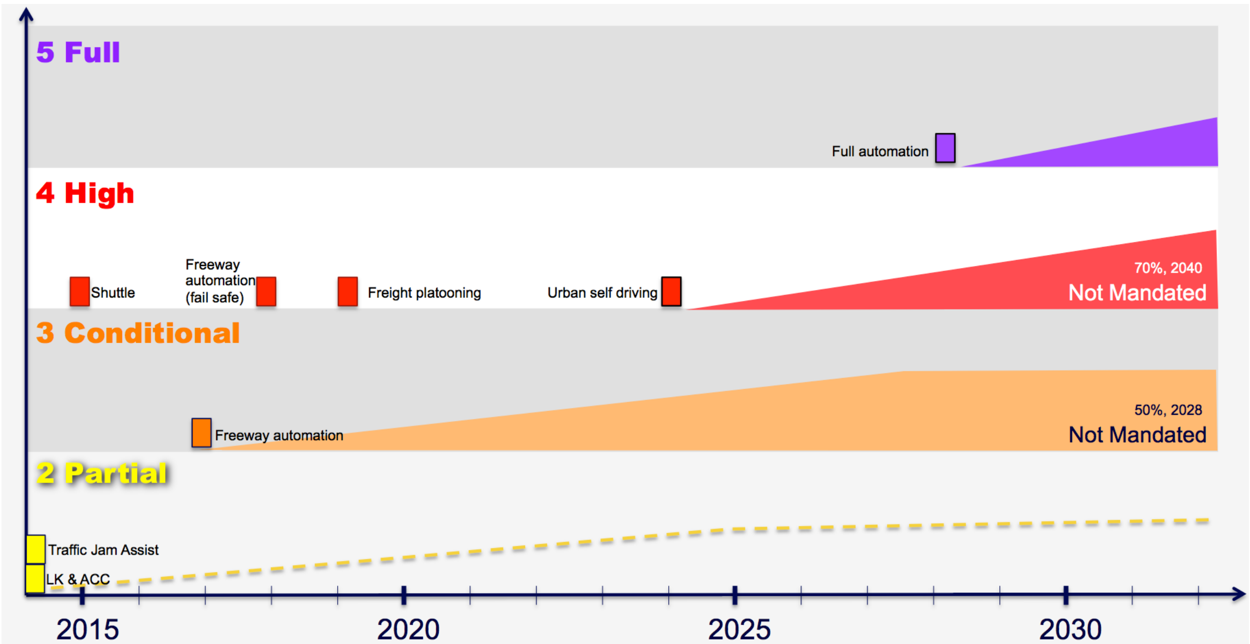

Figure 30. Expert Panel, First Quartile Market Introduction Forecasts, "Optimistic"

Automated Vehicles Milestones

In the first part of this survey, panelists were presented with a series of questions that assessed and captured their opinions regarding several milestones related to vehicle automation that are presented in the following table. They were also given an open ended section where they could express their comments regarding other technologies or milestones that needs/should be accomplished to assist with the advancement of the vehicle automation.

1) There is a great need to reduce the cost and size of sensors, including LIDAR, vision, and Radar. While OEM's are already investigating various LIDAR technology only ver time, it is likely that the cost of these sensors can be reduced, if more automated functions are introduced leading to high volume sales.
2) It is a major accelerator, if there could be a unified approach in designing and installing traffic signs and signals. Currently, many states follow somewhat different designs in the signs and signals they use which makes it challenging for an automated systems to identify and recognize them while travelling across states.
3) The above comments leads to another point that government needs to rethink the role of the aging infrastructure so that it could support the deployment of the automated vehicles. The infrastructure rethinking process could perhaps start by providing test beds that are capable of testing in a controlled environment (including fog, rain, shadows, crest and valley clothoid roads, etc...)
4) While many attempts are currently not so focused on the cyber-security side of automated vehicle technology, it is a formidable need to consider forward-compatible security systems, both at vehicle and SCADA levels.

Round 2; Question 1: In light of the results from round 1 of this survey shown below, please answer the following question: The list below represents a set of possible automated vehicle technology milestones that will be accomplished by the automotive industry in the United States. Please select the year that this milestone will be accomplished in the United States. For items in this list that believe should be removed or will never occur please indicate with "never" response options.

Table 10. Expert Forecast for Automated Vehicle Milestones

Automation Technology Milestones	Median Year	Percent of Panelists who said "Never"	Interquartile Range (25/75)		Average Level of Experience (3=High)
			25%	75%	
OEM's introduce vehicles with some automated capability to market that include pedestrian detection and recognition that can adequately function under most weather conditions.	2014.5	0.00%	2013	2017	2.33
OEM's introduce vehicles with some automated capability to market that include traffic signage detection and recognition that can adequately function under most weather conditions.	2015	0.00%	2013.75	2017.25	2.00
OEM's introduce vehicles with some automated capability to market that include cost-effective multi-return, all weather LIDAR sensors.	2016	4.35%	2013	2017	2.29
OEM's introduce vehicles with some automated capability to market that include vision technology to replace the use and function of Radar.	2014.5	20.00%	2013	2017.25	2.13
Truck OEM's introduce freight trucks with some automated capability that include vehicle platooning capabilities.	2019.5	0.00%	2017	2020	1.83
Industry introduces retrofit kits into the market that allow legacy passenger vehicles (i.e., without fully-automated functionality) to become Full Self-Driving Automated Vehicles (Level 4).	2025	56.52%	2024	2027.5	2.33

Policy Milestones (NHTSA Level 4)

Round 2; Question 6: What year will the milestone be accomplished (i.e., introduced to market)?

In this section, panelists were presented with a set of possible automated vehicle policy milestones that could be accomplished by U.S. federal and/or state government agencies. The table below, presents the responses gathered from panelists which is followed by several comments, indicating issues that were not addressed here and need to be considered:

Table 11. Expert Forecast of Policy Milestones

Milestones Market introduction	Year of Occurrence (Median)	Interquartile Range (25/75)		Never"
		25%	75%	
1) Federal regulators establish standards for testing and compliance of Full Self-Driving Automated Vehicles (Level 4)	2018	2018	2025	
2) A sufficient number of states establish legislation legalizing the operation of Full Self-Driving Automated Vehicles (Level 4) on roadways that enables cross-country travel (e.g., east coast to west coast, north to south)	2020	2018	2025	2
3) The first U.S. state establishes comprehensive insurance regulation for civil liability issues involving Full Self-Driving Automated Vehicles (Level 4) (e.g., who is liable for a collision)	2018	2017	2020	
4) An OEM offers fully insured Full Self-Driving Automated Vehicles (Level 4) sold due to their proven track record of safety	2025	2023	2030	3
5) The first U.S. state designates a dedicated highway lane for Full Self-Driving Automated Vehicles (Level 4)	2025	2020	2030	4
6) The first U.S. state government establishes legislation allowing citizens to ride legally in non-driver seating positions of Full Self-Driving Automated Vehicles (Level 4)	2030	2025	2035	
7) The U.S. federal government enacts consumer protection laws, data recording procedures, and defines data ownership rights in the context of data extracted from Full Self-Driving Automated Vehicles (Level 4)	2022	2019	2025	

- Two of the respondents strongly believed that any government involvement will be a hindrance to the advancement of the technology
- There is a need to establish acceptable, measurable accident rates (property, injury, fatal)
- Roll out of dedicated lanes for autonomous vehicles in a city center might be advanced by some smart cities in 2025 timeframe to promote enhanced mobility, safety and cleanliness.

- Policy on infrastructure responsibility to accomplish automated driving. Addendum's to road designs to support electric vehicle charging on road and automated vehicles
- There is a strong need to have government fund and advocate proof of concept testing – that helps in policy as well as engineering. Evidence will need to be gathered.

The milestone forecasts from the previous questions are summarized in the following chart. Note that improvements in vision and lidar detection, as well as, improvements in sensing capabilities around pedestrian and traffic sign detection are predominant in the next three years. Moving out to 2018 BC improvements in digital mapping for navigation and localization as well as related localization capabilities and GPS denied areas. We also see developments in the insurance industry for addressing automation as well as efforts to implement standards and compliance testing for the early freeway automation systems. This is all related to the potential mandate for connected vehicle systems that would assist in the downloading of digital maps as well as support warning systems and the coordination of vehicles for adaptive cruise control and platooning. Over the next five years we also see advances in freight platooning and intersection assist along with the introduction of vehicles with a cooperative adaptive cruise control. While the panel is relatively pessimistic about the potential for retrofit kits for automation if they are relevant we will perhaps see their introduction around 2023. In 2025 we will see the introduction of urban self driving systems as well as the potential birth of a new original equipment manufacturer. Around the same time we may see the OEMs taking on some responsibility for the insurance of the vehicles. In the 2030 timeframe we may see legislation enabling full automation.

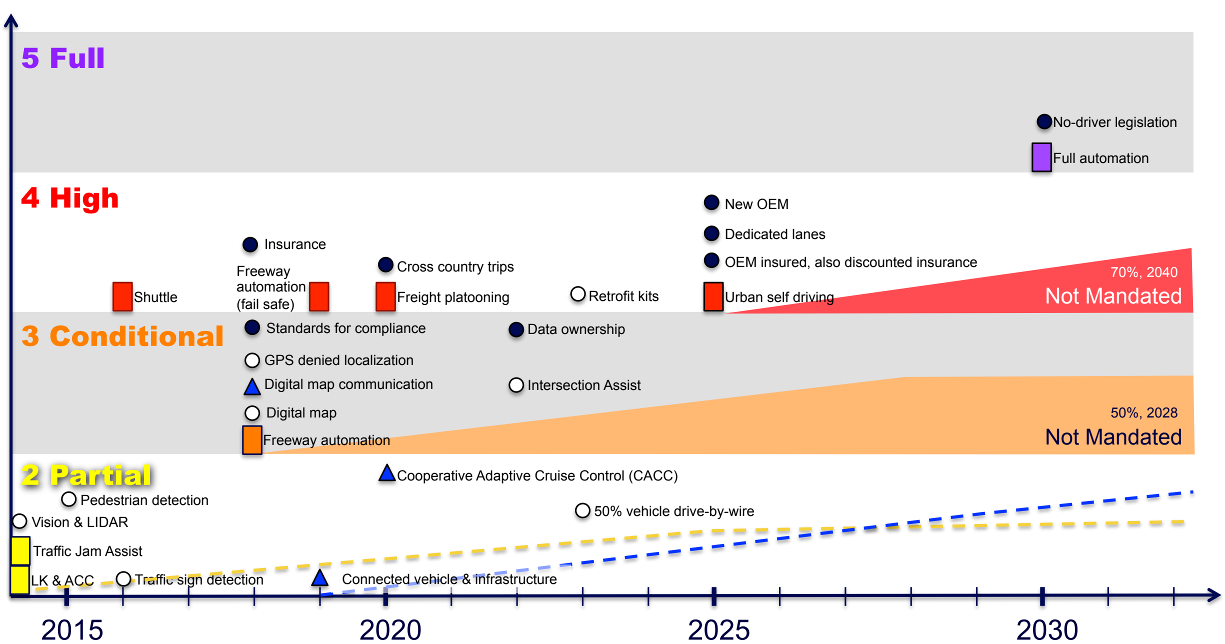

Figure 31. Expert Panel, Median Market Introduction and Milestones

Roadmap as Scenario

The events providing the core structure and timing of the for the scenarios are the expert forecasts of market introduction for automated freeway driving, platooning, automated shuttles, and the more advanced levels with high and full automation as summarized in Figure 2. The forecast team also received guidance from meetings with local public officials and citizens groups in the Seattle area including Puget Sound Regional Council, Washington State Department of Transportation, Housing and Urban Development, and Joint Base Lewis-McCord. These groups provided input on prevailing factors that would influence transportation in the region and throughout the Unites States over the course of the next thirty years. The critical external factors that will determine the future of transportation in the United States are (1) the legacy road infrastructure and land-use pattern providing a relatively inflexible geographic foundation for road transportation, (2) the stable and ageing "Stage 4" population structure that will have nearly 35 million adults over the age of eighty in 2050, (3) the inescapable force that global warming will place on the United States to limit fossil fuels and support alternatives that includes electric propulsion of vehicles, and (4) scientific, technological, and engineering advances in alternative energy, robotics, and communication.

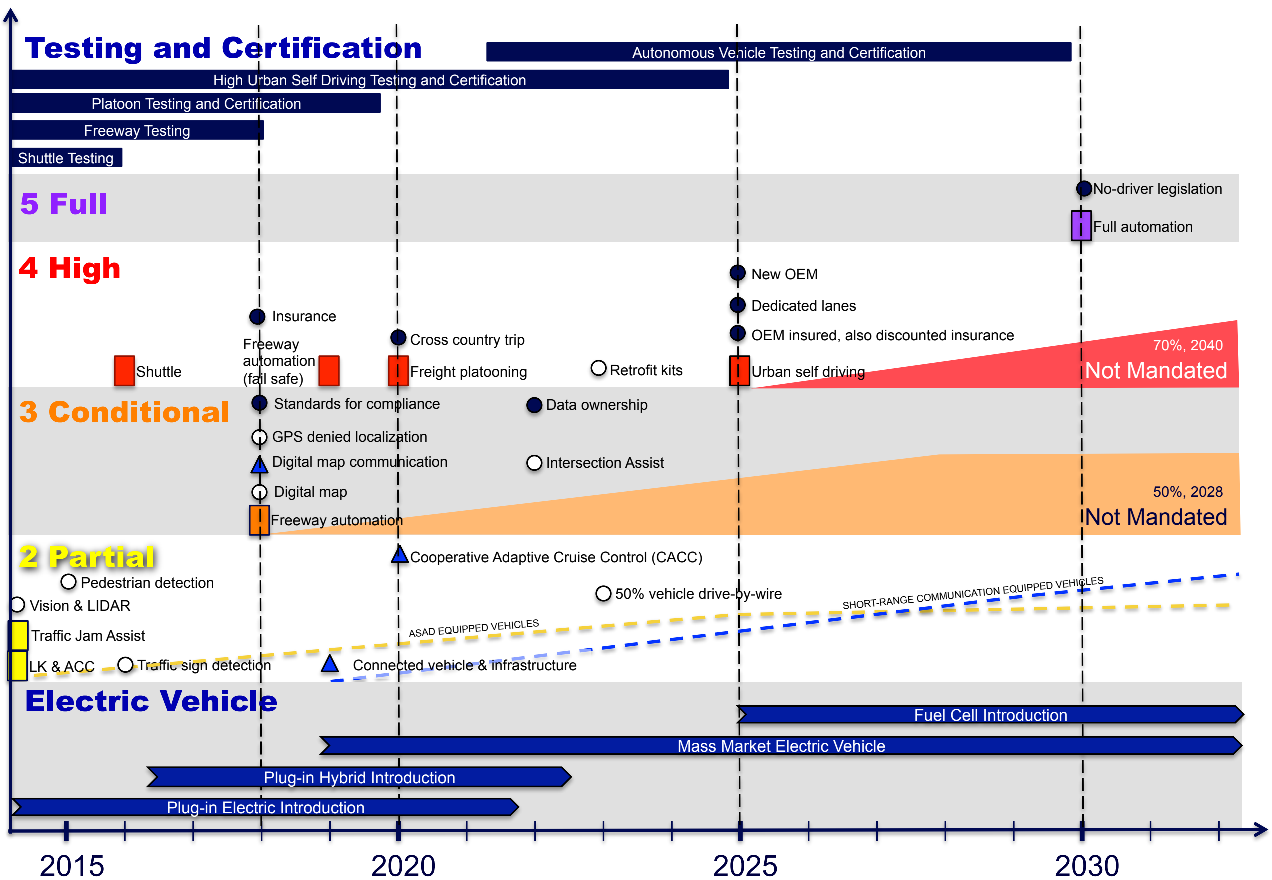

Figure 32. Full Picture and for Automated, Connected, and Electric Vehicle Roadmap to Sustainable Mobility

While there may be some advances in the innovative use of existing infrastructure like, for example, investment in inductive charging in highway lanes dedicated electric vehicles with, say, platooning capabilities, it is unlikely that a significant transformation to intercity transit will take hold in the United States given the decentralized population, connectedness through social media, and the pervasiveness of existing road infrastructure and land-use patterns. Furthermore, the primary thesis of the forecast is that the automobile will transition to electric, automated, and connected enabling the more sustainable and economically efficient use of the existing road infrastructure and possible sharing of safer and more lightweight vehicles. However, should there be the pervasive adoption of vehicle-to-infrastructure communication along with aggressive road pricing policies throughout the United States one could envision a gradual and long-term evolution to marginal cost pricing of road transportation taking into account external factors like emissions and congestion that could make transit more feasible especially in high density areas. Nevertheless, given the thirty-year time we assumed road pricing would help place a limit on growing demand and that any shift from the automobile to additional transit would be marginal.

Present through 2018

In the period from today until 2018 the market is characterized by the introduction of new vehicles with driver assist features including blind spot detection, automated cruise control, and traffic jam assist, among others from a full range of active safety features. These features are introduced primarily on high-end luxury vehicles and with substantial price decrease over this period by 2018 a functional package of driver assist features can be added to a moderately priced vehicle for less than $1000. The demand for these packages of driver assist options increases as the price falls and by 2018 nearly 20% of the new vehicles sold in the United States have some form of optional radar and/or vision-based collision warning and/or pedestrian detection system. In the meantime the higher-end luxury vehicles are getting optional features like low speed traffic jam assist and partial automation combining lane keeping and adaptive cruise control for highway driving. One of the technical issues that will be addressed and resolved is increasing the reliability of lane tracking and centering in challenging infrastructure and weather environments. The bottom line is that the new vehicles with standard and optional active safety that are coming to market are safer than the previous generation of vehicles, and despite drivers' inattention and distraction from consumer electronics, the rate of injury and fatality from crashes continues to drop.

Also during this period we find the operational testing and early introduction of automated lightweight pedestrian zone shuttle vehicles that travel and are capable of safely managing trajectories through pedestrian traffic at low speeds. When asked about the level of safety for public use the 75% of the panel indicated that the systems should be at least twice as safe as a human driver. This response pattern was also supported by AVS and SAE. However, the AVS respondents also indicated that society will accept automated vehicles occasionally causing crashes, whereas, only 52% of the SAE respondents found it acceptable. Early deployments may use dedicated and restricted lanes for shuttle travel. These early shuttle deployments will provide an opportunity to test out automated vehicle maneuvers at low speeds and possibly assess the benefits of inductive charging of automated electric vehicles with precision driving over dedicated charging infrastructure. The price of the early automated shuttle vehicle is comparatively high due to the more advanced and more expensive LIDAR, vision, and localization technologies required for dynamic object detection and precise trajectory planning, control and navigation in densely mapped point cloud environments. However, because this is the testing ground and practice field for urban automation that will come ten years later and manufacturers may provide extensive discounts or establish partnerships to implement these technologies at acceptable costs to the facility owner or end user in order to gain experience and improve the systems over time. Shuttle applications are likely to be more common in Europe and Asia because of populations with higher densities, more conducive urban settings, and well as more accepting regulatory environments. Nevertheless, in the United States shuttles may be introduced to military bases where public interest is represented by the military and only later to pedestrian malls and shopping centers, theme parks; pedestrian zones in city centers, neighborhoods with limited vehicle access, and other places where people need to travel yet the shuttles are not exposed to conventional high-speed road vehicle traffic.

Most of the shuttles will be designed as small lightweight limited-distance electric vehicles with a size similar to electric golf carts or somewhat larger for multiple passengers. Yet, they will have a technology mix similar to future higher speed highway and urban vehicles and lessons learned will help develop the future generation of high and full automated systems. The focus of technical advances during this period are primarily safety oriented, yet, automotive research and development is also addressing the added convenience for drivers with the operational testing of freeway automation and automobile and truck platooning along highways. Others are continuing to test and develop more highly automated systems for automated driving in urban areas.

The rate of advance during this period will depend on public policy and the attention to transportation infrastructure, vehicle safety, oil production, gas taxes, science and technology, and climate change in the 2016 election cycle. Following the 2016 election and moving into the middle of the term some serious attention will need to be devoted to these climate change and vehicle automation is complementary to if not an essential part of this picture. The U.S. DOT automation program will position industry and public agencies for the wide-scale deployment of Level 2 vehicle systems that improve safety, mobility and reduce environmental impacts by the end of the decade with special attention devoted to human-in-the-loop systems and safety assurance, and methods for testing and evaluating higher levels of automation.

Scenario for 2018 through 2020

The time period form 2018 to 2020 is noteworthy for the introduction Level 3 systems equipped with automated freeway driving that enable drivers to engage in other activities on their commute while the vehicle takes over control. According to both the TRB and SAE respondents these would be offered to the general public as original equipment (i.e., by the aftermarket). The automotive manufacturers who have made announcement of their plans for introducing "autonomous" vehicle systems by 2020 have implicitly, or in some cases unambiguously, described the systems as Level 3 or Level 4 highway automation. In concept systems perform at full speed like advanced cruise control. The Level 3 systems rely on vision and GPS and only engage in the best of conditions and require the driver to monitor the driving environment. Many of the respondents (54%) identified this need for driver intervention as not practical. The Level 4 systems will be more expensive because they have more advanced LIDAR and/or vision sensors and digital mapping along with the management of point clouds for precise localization. There is a significant technological and price jump between the Level 3 and Level 4 systems and the projected timing of introduction is so small that there will be public debate over delaying the jump on functionality form traffic jam assist at slow speeds to full freeway automation at higher speeds in order to avoid attention management or performance issues with drivers in Level 3 system.

With the introduction of freeway automation in 2018 we also see advances in the downloading and continuous updating of digital maps for accurate navigation and localization of vehicles even in GPS denied areas. This becomes a viable business limited to selected highways and supported by advanced cellular technology and this coincides with early short-range communications being mandated on all new vehicles. We also see the establishment of standards for compliance and certification of systems for freeway automation and freight platooning. According to our panel the vehicle-to-vehicle investment will also have a significant payoff in future years to support SAE Level 5 automation.

Freeway automation systems improve rapidly on the high end with the introduction of more reliable digital mapping, advanced optics, point-cloud localization, system redundancy, and new systems for failsafe operation enabling the driver to disengage in the driving task and attend to other matters while in the driver seat. The market for vehicles equipped with driver assist systems continues to grow along with the enthusiasm and high demand for the new vehicles with the more expensive full-speed freeway automation option. The federal mandate for communication dedicated to safety applications has a significant impact on reducing crashes in equipped vehicles and the numbers continue to grow. As the market for driver assist functionality as well as freeway automation continues to grow there is the introduction of new no-fault insurance arrangements adjusting to the increases in safe driving as well as recognizing the vehicles increasing role for monitoring the driving environment and controlling the vehicle. The vehicle electronic data recorders collect an expanded dataset that is most definitive in describing crash dynamics and conditions. According to the panelists the manufacturer will be responsible for system malfunctions leading to crashes. However, nearly 50% also indicated that some form of no-fault insurance may also facilitate the adoption of this technology.

The market for freeway automation in passenger vehicles grows rapidly with the introduction of the higher end systems because vehicle owners can safely devote their attention to the complementary portable or embedded telematics that is also a growing market. This union of high-end automation and embedded telematics is a market winner and a tipping point in the market for those who can afford the systems. Drivers' education requires training and road testing in highway automation and self-parking.

In the meantime the testing and certification standards for truck automation and cooperative freight platooning take center stage during this period. One can foresee a milestone like a small platoon of trucks engaging in a landmark convoy between Los Angeles and New York City. This marks the ability of automated driving nonstop across the United States and has great public appeal because of reductions in emissions and energy efficiency supporting the global war on climate change. During this time there is a related growing movement to enable cars to platoon and to increase the electric vehicle-charging infrastructure including inductive charging on selected highways that is made more effective through the precise maneuvers of automated vehicles.

Freight platooning is developed around a standard for cooperative adaptive cruise control (CACC) and also addresses the problems of vehicles entering and exiting the platoon, platoon lane changes, and the integration of platooning trucks other traffic along the freeway. The communication systems that support CACC also support the updating of the digital mapping that enables travel in GPS denied areas. Both long-range and short-range communication systems support the updating of digital maps. Furthermore, parallel standards for road or congestion pricing communication systems are finalized and for new vehicles along with alternative aftermarket systems. Pricing no only helps to offset the loss of gas taxes as electric vehicle catch on but also anticipates the increased demand induced by highway automation and helps to control related increases in highway congestion.

While the focus for automated vehicle systems during this period centers on freeway driving it has little connection with the developments during this period with plug-in electric and hybrid vehicles. However, universities are engaging in research in inductive charging along exclusive lanes of the freeway that take advantage of the lane keeping features to optimize charging capabilities. Also, the market for automated shuttles is continuing to grow and older cities are introducing them in new pedestrian zones developments are using them in their design of new Greenfield communities. Over time the vehicles are becoming more capable of driving safety and reliably at higher speeds and at the same time the overall comfort of the automated ride is improving dramatically. One of the nicer features of the shuttle vehicles is their design for quick transfers at parking and transit stops which makes it easy for seniors, children, and mobility disabled to gain access to the city center. That is, vehicles are harmonizing through control centers to increase the efficiencies of individual trips as well as coordinating with transit. But overall by the end of this period the market penetration of automated systems is still quite low with less than fifty percent of vehicles equipped with driver assist and conditional automation just recently being introduced to the market.

Scenario for 2020 through 2025

From the year 2020 through the year 2025 there's growing public concern for the continued emissions of hydrocarbons into the atmosphere as pollution from all sources is getting attention for stricter management. There is been significant reductions in the cost of batteries for electric vehicles although range continues to be an issue for mass adoption of hybrids and battery electric vehicles. There is continued interest in the prospect for designated lanes supporting both freeway automation and inductive charging for longer trips. The market for battery electric (e.g., Nissan Leaf) and plug-in hybrid electric (e.g., Chevy Volt) and fuel cell electric (e.g., Toyota,

2015) continues to grow as the price of batteries comes down and the prices of electric vehicles become competitive without subsidies.

This is a period of intensive testing and development of self-driving vehicles that can manage urban environments. Research and development testing in the United States is centered on shuttle communities, public tests of vehicle platooning, and private tests in highway and urban settings. The miles of self-driving vehicle are accumulating and digital mapping services are helping with road asset management for states as well as becoming available for assisting automated vehicles on more of the highways and surface streets in the United States. Unified strategies for testing and evaluation employing integrated simulation and test track maneuvers are helping to increase system reliability and overall confidence in the performance of the systems. In cooperation with the automotive industry the National Highway Traffic Safety Administration (NHTSA) develops and approves a testing and compliance protocol for OEMs to introduce high automation in the latter half of the decade. Early tests demonstrate their safety and selected manufacturers are designing self-driving electric vehicles for urban markets.

Nearly 50% of the vehicles coming to market in 2025 have the required drive-by-wire capabilities for steering, throttle, and braking. Similarly, the number of vehicles with driver assist features entering the market is approaching fifty percent along with similar numbers for the mandated connected vehicle capability. The number of crashes has come down to fifty percent of the number a decade back with proportional reductions in injuries, fatalities, and property damage. Still, driving a vehicle has its risks because there are still vehicles on the road without driver assist and/or automation. It is still too early to reduce the weight by reducing structural, active, and passive safety components. It is also unlikely that the blind or elderly or other mobility disabled populations will get around urban environments in self-driving vehicles.

Furthermore, the number of vehicles with automated freeway commuting capability is continuing to grow with close to 35% of the vehicles being sold with this feature of the year 2025. The demand for vehicles with freeway automation is similar to the demand for vehicles with cruise control back in 2010. It is an option that customers want to think age in any freeway driving. Also, the number of freeway traffic accidents and related delays continue to plummet and this has measurable impact on increasing vehicle miles traveled and continuing growth of outlying suburban areas around major cities. this is being managed in a number of metropolitan areas through automated toll collection and user fees that are supported through the increasing number of drivers with connected vehicle technologies. The metropolitan areas that are assessing fees the drivers with new cars have the ability to use embedded systems and drivers of older cars can purchase aftermarket devices that provide here I am messages that increase the vehicle safety as well as provide the ability to assess fees.

This period comes to a close with the much-anticipated introduction of vehicles will "self-driving" capabilities for urban areas. These vehicles can chauffeur their riders from one part of town to another and travel along the freeway without a human driver most of the time. However, in complicated situations what might be perceived as dangerous travel conditions the vehicle requires a driver. The automated driving system will only operate in environments conducive to event-free driving. Furthermore, although the vehicle can fail safely and come to a stop in what is perceived as a safe location the vehicle relies on the driver in many cases to take over control and drive from one place to another.

Scenario for 2025 through 2030

Vehicles with high automation and the ability to travel both on freeways and in urban environments are introduced to the market in in this time period and are accompanied by no-fault insurance policies designed specifically for high automation. Although this is a low-volume feature offered on high-end luxury vehicles in the beginning the market increases steadily so that close to 30% of new vehicles have this is a feature by 2035. Many of these new self-driving vehicles are also electric vehicles that can take advantage of inductive charging sites through the precise sensing of the environment and looked locating the vehicle and the appropriate position. These self-driving vehicles also have freeway automation and add to the number of vehicles on the freeways with automated commuting features. Electric vehicles with inductive charging and automated freeway driving capabilities can travel along the lanes that are dedicated to both charging and automated driving. While commuters enjoy these vehicles the freedom to devote their time to other non-driving tasks the overall demand is managed through automatic payments of user fees in most metropolitan areas. Some new vehicles are introduced to market with fuel-cell technology and there is a high demand for these vehicles in selected areas with the appropriate infrastructure. In the meantime consumers are hearing about the new vehicles that will be introduced that can taxi them from one place to another without a driver. Public officials are working on new legislation to enable the self-driving taxi expected in 2030. These vehicles will also have the ability to drive to locations without a human onboard.

Although close to 50% of the vehicles on the road have active safety systems that are making a serious dent in the number of traffic accidents and related delays on the roadway, number of customers still do not have an interest or feel the need for driver assist her vehicle automation. So, while the number of accidents has decreased significantly they have not been eliminated entirely, and drivers of non-automated vehicles cause most of the traffic accidents. This is a well-known fact because the automated vehicles have electronic data recorder systems that provide considerable detail of situations leading up to an accident. The data recorders also help in the case of liabilities and insurance related crashes of automated vehicles. This data provides clear evidence that human error and driver distraction continues to be the number one cause of crashes. The automated vehicles are rarely at fault when crashes occur.

Scenario for 2030 through 2040

The fully automated and self-driving chauffeur or taxi vehicle is introduced to the market in the 2030 timeframe an possibly as later as 2035. Much of the technology for these vehicles has been developed and tested over a period of about 20 years with the automated shuttle, automated commuter vehicle, the freight platooning systems, and more recently by the urban self driving vehicle, and finally by vehicles designed for special applications like manufacturing and mining. Special legislation is required to enable these vehicles to be driven without a driver in states that allow them. The technology and systems in the fully automated vehicle are an outgrowth and continuation of the technology and systems used in the urban self-driving vehicles that were introduced five years earlier. Over the last five years the on-road testing of the autonomous systems as well as the highly automated urban self driving systems has brought the technology to a point where the vehicles can drive themselves.

Conclusion and Summary

The scenario or roadmap to sustainable personal mobility is summarized in Figure 4 below with path to electric vehicles represented by the green boxes, the path to vehicle automation represented in blue, and the path to connected vehicles represented in brown.

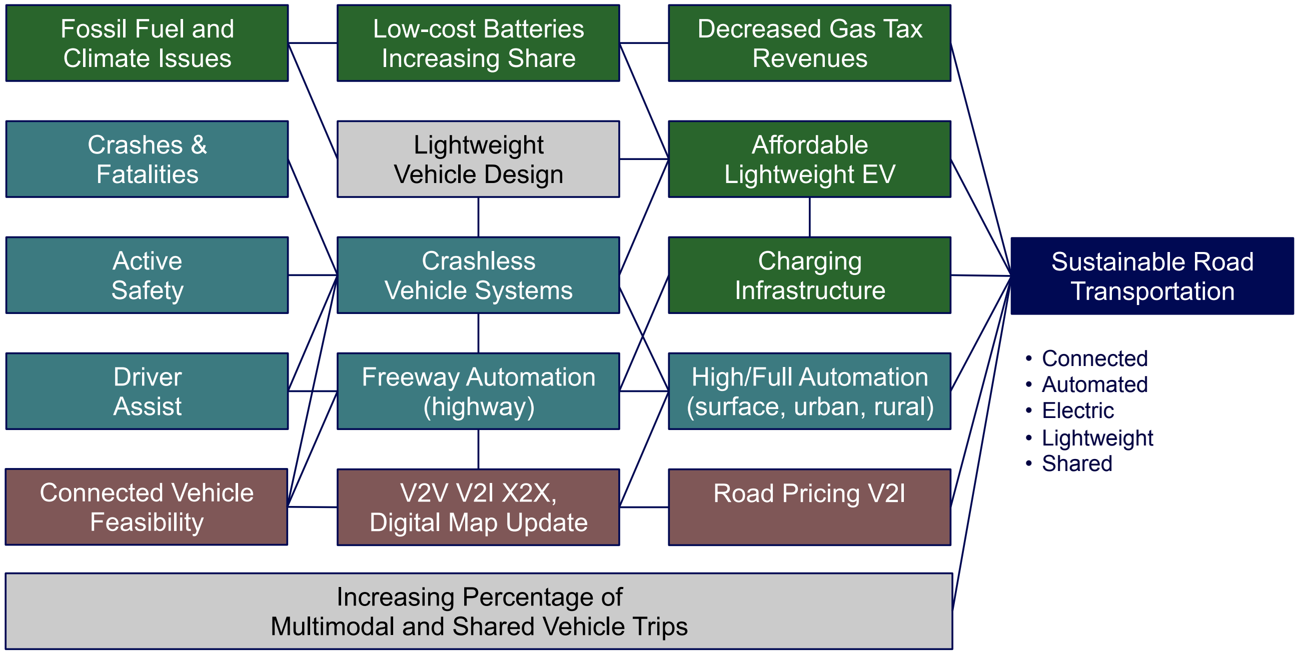

Figure 33. Roadmap to Automated, Connected, and Electric Vehicle Sustainability

The percentage of revenues for road construction and maintenance from user fees continues to grow along with the increasing percentage of vehicles that have mandated short range communication systems. Most vehicles on the roadway now have communication and debiting systems that support charges for their use of the road. The percentage of electric vehicles also continues to grow along with a number of fuel cell vehicles in selected areas of infrastructure.

While the omission of hydrocarbons continues to be an issue with worldwide production of energy the amount of local pollution from automobiles to drop dramatically in the use of renewable energy sources continues to increase.

The roadmap is summarized in this figure. We start with automobiles based on the internal combustion engine and the human driver in control with all of the related consequences including driver error leading to crashes, property damage, injuries, fatalities, and traffic delay and emissions from the gasoline powered engine resulting in emissions of hydrocarbons and dependence on the import of foreign oil. Both passive and active safety systems are relatively developed to protect the driver. Alternative energy sources for the motor vehicle is promising if not practical or cost-effective at this stage.

Over the course of the next five years we can expect dramatic improvements in active safety technology creating a pathway for a vehicle that will not crash. The driver will be warned or the vehicle will take over before crash occurs or in the event of a crash the vehicle rate will reduce the impact. However during the same period of five years new technologies will be introduced to monitor the vehicle environment and control the vehicle to effectively replace the driver in specific situations. The self driving shuttle will be introduced as well as vehicles that drive themselves on the highway. The connected vehicle will enable the upload of digital maps for navigational localization as well as longer distance communications with other vehicles in the traffic management system. Automotive engineers will be working to make these safer vehicles more lightweight fuel-efficient all the same time adopting low-cost battery and charging technologies.

Moving further into the future we will see highly automated vehicle that can drive themselves on the freeway and in the city and possibly guide themselves along inductive charging paths on dedicated lanes of the highway. While the benefits of increased safety and productivity due to automation may lead to increased demand and a willingness for drivers to take longer commutes and purchase homes further out in the suburbs the connected vehicle technology will enable the state Department of Transportation and regional councils of government to charge user fees to manage the demand and allocate costs. This demand management technology may offset the increased demand due to savor and less stressful automated driving. As the price comes down for batteries and alternative sources of energy this automated, connected, and electric vehicle alternative will create a path to sustainable automotive transportation

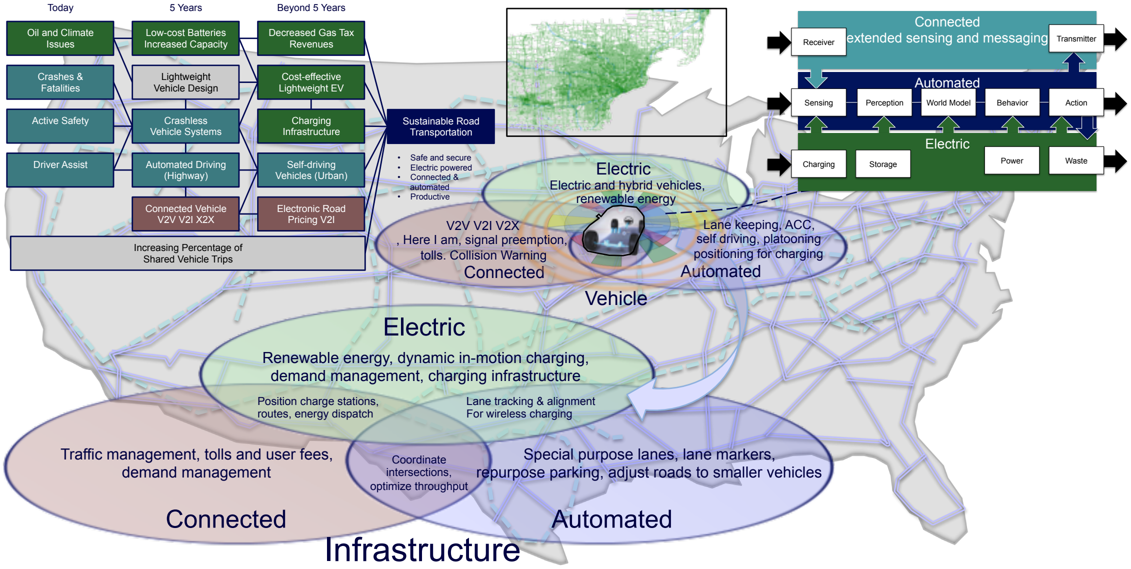

Figure 34. Cyber-Physical System for Vehicle and Infrastructure Integration of Automated, Connected, and Electric Vehicle Systems

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Glossary

Automation: The capability of a machine or its components to perform tasks previously done by humans. Usually accomplished by a subsystem of a larger system or process, performance of tasks can be cued by humans or a point in the process. Examples are an autoloader in an artillery system or machine welding of parts on an assembly line

Automated Driving System (ADS): This refers to the hardware and software that is collectively capable of performing all aspects of the dynamic driving task for a vehicle (whether part time or full time). (SAE J3016)

Autonomous: A mode of control of an automated vehicle wherein the vehicle is self-sufficient. The autonomous vehicle is given its global mission by the human, has been programmed to learn from and responding to its environment, and operates without further human interventions.

Autonomous Vehicle: A automated vehicle (sometimes called a self-driving car, an automated car or an driverless car) is a robotic vehicle that is designed to travel between destinations without a human operator. To qualify as fully autonomous, a vehicle must be able to navigate without human intervention to a predetermined destination over roads that have not been adapted for its use.

Behaviors: Following rules during a mission. These behaviors may include rules of the road such as intersection progression for ground vehicles or docking for surface vehicles. Often, rules and guidelines may conflict. This includes waypoint following. Specific behaviors include follow the leader, area clearance, teleoperated (remote) control, obey rules of the road, intersection behaviors (precedence, queuing). multilane traffic, oncoming traffic, passing disabled/moving vehicles, lost communication procedures, automatic rerouting, re-traverse and/or teach and repeat a route, retro-traverse: return to point of origin along the previously travelled path, detecting and estimating road surfaces, road following, detecting and classifying obstacles (people, vehicles, others), detecting and interpreting regulatory traffic signs, etc.

Classes of vehicles: The Joint Robotics Program Office of the United States Department of Defense postulates several classes of UGVs, based upon weight: Micro: < 8 pounds, Miniature: 8 – 30 pounds, Small (light) 31- 400 pounds • Small (medium) 401 – 2,500 pounds, Small (heavy): 2,500 – 20,000 pounds, Medium: 20,001 – 30,000 pound, Large: > 30,000 pounds

Computation for Sensors: Calculates observed entity attribute values generated by the grouping hypothesis

Conditional Automation (Level 3): Conditional Automation is the part-time or driving mode-dependent performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene. Conditional automation requires a human driver to initiate an automated driving system at the appropriate point during a trip and requires a human driver to resume the dynamic driving task when s/he receives a request to intervene (e.g., due to a vehicle or system malfunction or a change in driving conditions that exceed the automated driving system's driving mode-dependent capability). As a technical matter, a human driver need not monitor the automated driving system's performance while it is engaged, but must be prepared to resume the dynamic driving task when the automated driving system issues a request to intervene. A conditional automated driving system will alert (i.e., by issuing a request to intervene) the human driver of the need to resume the dynamic driving task with sufficient time for a typical human driver to respond appropriately. An "appropriate" response by a human driver to a request to intervene may vary depending upon immediate circumstances (e.g., steering, braking, or simply maintaining current input levels), but otherwise entails the timely, safe and correct performance of the dynamic driving task for the prevailing circumstances. An example is a vehicle equipped with an automated driving system capable of performing the complete dynamic driving task in low-speed traffic, such as in stop-and-go urban or freeway traffic. (SAE J3016)

Cooperative Algorithms: The ability of two or more automated vehicles to share data, coordinate their maneuver and perform tasks synergistically

Data and Network Structures: State variables, attributes, entity frames, relationships, images, terrain, rules, equations and recipes

Data Link: The means of connecting one part of the automated vehicle system with another part of the system for the purposes of transmitting and receiving data. Examples of technologies used as automated vehicle data links are radio frequency, fiber optics and laser

Detection, Recognition, Classification: Determines the correlation or match between estimated attributes of entities observed in the real world and corresponding attributes of entity classes stored in the system's knowledge base

DSRC/WAVE - Dedicated Short Range Communications; a wireless (radio) communications approach that enables short range communications between vehicles and between vehicles and the roadside for a variety of purposes.

Drive: Drive means to operate a vehicle on a public or private roadway at any point at or between an origin and a destination, whether or not the vehicle is in motion (SAE J3016)

Driver Assistance (Level 1): Driver Assistance is the part-time or driving mode-dependent execution by a driver assistance system of either steering or acceleration/deceleration with the expectation that the human driver performs all other aspects of the dynamic driving task. (SAE J3016)

Driving Mode: A driving modes is a type of driving scenario with characteristic dynamic driving task requirements (e.g., expressway merging, high speed cruising, low speed traffic jam, etc.). (SAE J3016)

Dynamic Driving Task: A dynamic driving task is a real-time function required to operate a vehicle in on-road traffic, excluding the selection of destinations and waypoints (i.e., navigation or route planning) and including without limitation: (SAE J3016)

- Object and event detection, recognition, and classification;
- Object and event response;
- Maneuver planning;
- Steering, turning, lane keeping, and lane changing;
- Acceleration and deceleration;
- Enhancing conspicuity (lighting, signaling and gesturing, etc.).

Filtering/Recursive Estimation for Sensor Data: Computes best estimates (over space/time window) of entity attribute values based on correlation and differences between predicted and observed attribute values. Also statistical properties such as confidence/covariance in/of estimated values are computed

Full Automation (Level 5): Full automation is the unconditional, full-time performance by an automated driving system of all aspects of the dynamic driving task under, at minimum, all roadway and environmental conditions that can be managed by a human driver, including the ability to automatically bring the motor vehicle into a minimal risk condition in the event of a critical vehicle or system failure, or other emergency event. As a technical matter, a human driver need not monitor the automated driving system's performance. When the automated driving system reaches the limits of its functional capabilities, it will restore the vehicle to a minimal risk condition automatically. An example is a vehicle with an automated driving system that, once programmed with a destination, is capable of fully performing the dynamic driving task throughout complete trips on public roadways, regardless of the starting and end points or intervening road, traffic, and weather conditions. (SAE J3016)

GSP - Global Positioning System Global Positioning System; a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations. GPS calculates positions accurate to a matter of meters.

High Automation (Level 4): High automation is the part-time, driving mode-dependent, or geographically-restricted performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver fails to respond appropriately to a request to intervene. High automation generally requires a human driver to engage an automated driving system at the appropriate point during a trip (e.g., a human driver may activate the automated driving system during a specific driving mode, such as freeway driving, for which the high automated driving system is designed). Examples of exceptions to the general case: high automation parking application for which a human driver is not present in the vehicle during the maneuver, high automation shuttle system (with or without a human driver) that is geographically restricted to operation on a closed or semi-closed campus (e.g., residential community, military base, etc.). As a technical matter, a human driver need not monitor the automated driving system's performance while it is engaged, but should in the general case be prepared to assume performance of the dynamic driving task when the automated driving system issues a request to intervene. A high automated driving system will alert a human driver several seconds in advance of the need to resume the dynamic driving task (i.e., by issuing a request to intervene); however, the automated driving system is capable of restoring the vehicle to a minimal risk condition automatically if a human driver fails to resume the dynamic driving task when prompted. This capability to automatically restore the vehicle to a minimal risk condition is the only difference between high automation and conditional automation, above. (SAE J3016)

Human Driver: A human driver is the person who drives a particular vehicle, and who, in a vehicle equipped with an automated driving system, exchanges the dynamic driving task with such a system as necessary during vehicle operation. (SAE J3016)

Human-machine interface: The means by which the human operator interacts with the automated vehicle system. It includes the software applications, graphics and hardware that allow the operator to effectively give instructions to or receive data from the automated vehicle

Intelligent Mobility: Intelligent mobility, or the ability to move up and over obstacles, avoid obstacles in the vehicles path, and to move in novel ways using advanced locomotion and artificial intelligence is an inherent requirement in all future robotic systems and will support a range of evolving requirements

Knowledge: Data and info structure representing situational status, events and the dynamic world model

Line-of-sight: (1) Visually, a condition that exists when there is no obstruction between the viewer and the object being viewed. (2) In radio frequency communications, a condition that exists when transmission and reception is not impeded by an intervening object, such as dense vegetation, terrain, man-made structures or the curvature of the earth, between the transmit and receive antennas

Minimal Risk Condition: This refers to a low risk motor vehicle operating condition to which an automated driving system automatically resorts upon either a system failure or a failure of a human driver to respond appropriately to a request to take over the dynamic driving task. NOTE: A minimal risk condition will vary according to the type and extent of a given failure. A minimal risk condition could entail automatically bringing the vehicle to a stop, preferably outside of an active lane of traffic (assuming availability). (SAE J3016)

Mission Planning: The Mission Planner component is the coarsest level of decision planning within the software architecture. The Mission Planner is responsible for determining which waypoint segments the vehicle should travel to complete a mission. The Mission Planner uses a-priori information such as terrain profiles, road networks, and information gathered during missions. After processing, the Mission Planner outputs a series of waypoints to the Behaviors module.

Monitor: Monitor means the activities and/or automated routines that accomplish comprehensive object and event detection, recognition, classification, and response preparation, as needed to competently perform the dynamic driving task. NOTE: When driving vehicles that are not equipped with automated driving systems, human drivers visually sample the road scene sufficiently to competently perform the dynamic driving task, while also performing secondary tasks that require short periods of eyes-off-road time (e.g., adjusting cabin comfort settings, scanning road signs, tuning a radio, etc.). Thus, monitoring does not entail constant eyes-on-road time by the human driver. (SAE J3016)

Motor Vehicle: A motor vehicle (or vehicle) refers to a vehicle driven or drawn by mechanical power and manufactured primarily for use on public streets, roads, and highways, but does not include a vehicle operated only on a rail line. [Source: 49 U.S.C. § 30102(a)(6)]

Navigation: The process whereby a UXV makes its way along a route that it planned, that was planned for it or, in the case of teleoperation, that a human operator sends it in real time

No Automation (SAE Level 0): No automation is the full-time performance by the human driver of all aspects of the dynamic driving task. (SAE J3016)

Non-line-of-sight: (1) Visually, a condition that exists when there is an obstruction between the viewer and the object being viewed. (2) In radio frequency communications, a condition that exists when there is an intervening object, such as dense vegetation, terrain, man-made structures or the curvature of the earth, between the transmit and receive antennas, and transmission and reception would be impeded. Non-line-of-sight communications implies communications across this normally non-line-of-sight terrain/distance. An intermediate ground, air, surface or space-based retransmission capability may be used to remedy this condition

Obstacle avoidance: The action of a UXV when it takes a path around a natural or manmade obstruction that prevents continuation on its original path

Obstacle detection: The capability of a UXV or its operator to determine that there is an obstruction, natural or man-made, positive or negative, in its path

On-road: This refers to public roadways that collectively serve users of vehicles of all classes and automation levels (including no automation), as well as motorcyclists, pedal cyclists, and pedestrians.

OEM – Original Equipment Manufacturer

Partial Automation (Level 2): Partial automation is the part-time or driving mode-dependent execution by one or more driver assistance systems of both steering and acceleration/deceleration with the expectation that the human driver performs all other aspects of the dynamic driving task. (SAE J3016)

Perception: Transformation of sensor signals into knowledge about situations and events in the real world

Remote Control: A mode of control of a UXV wherein the human operator, without the benefit of video feedback, directly controls on a continuous basis the actions of the UXV using visual line-of-sight cues

Request to Intervene: This is a notification by the automated driving system to a human driver that s/he should promptly begin or resume performance of the dynamic driving task. (SAE J3016)

Situation: A set of relationships existing between entities in the real world

Situational awareness: A situated creature or robot is one that is embedded in the world and does not deal with abstract descriptions but, through its sensors with the here and now of the world, can directly influence its behavior

Testbed – A system representation consisting of vehicles, devices, and systems including actual hardware and/or software and computer models or prototype hardware and/or software for testing and evaluating a complete systems or components of a system.

Transceiver – The transmitter-receiver transmits and receives signals.

Trip: A trip is the traversal of an entire travel pathway by a vehicle from the moment it is turned "on" at a point of origin to when it is turned "off" at a waypoint or destination. (SAE, J3018)

USDOT –United States Department of Transportation; a Cabinet-level Department that exists to serve the United States by ensuring a fast, safe, efficient, accessible, and convenient transportation system that meets our vital national interests and enhances the quality of life of the American people, today and into the future.

Use Cases – A use case is a description of a system that captures a goal-oriented set of interactions between external actors and the system under consideration. Actors are parties outside the system that interact with it; for example, system users. Use cases capture who (actor) does what (interaction) with the system, for what purpose (goal) without dealing with the internal working of the system itself. A complete set of use cases specifies all the different ways to use the system, and therefore defines all behavior required of the system, bounding its scope.

Waypoints: Intermediate locations through which a vehicle must pass en route to a particular destination

Waypoint navigation: The process whereby a vehicle makes its way along a route of planned waypoints that it planned or were planned for it

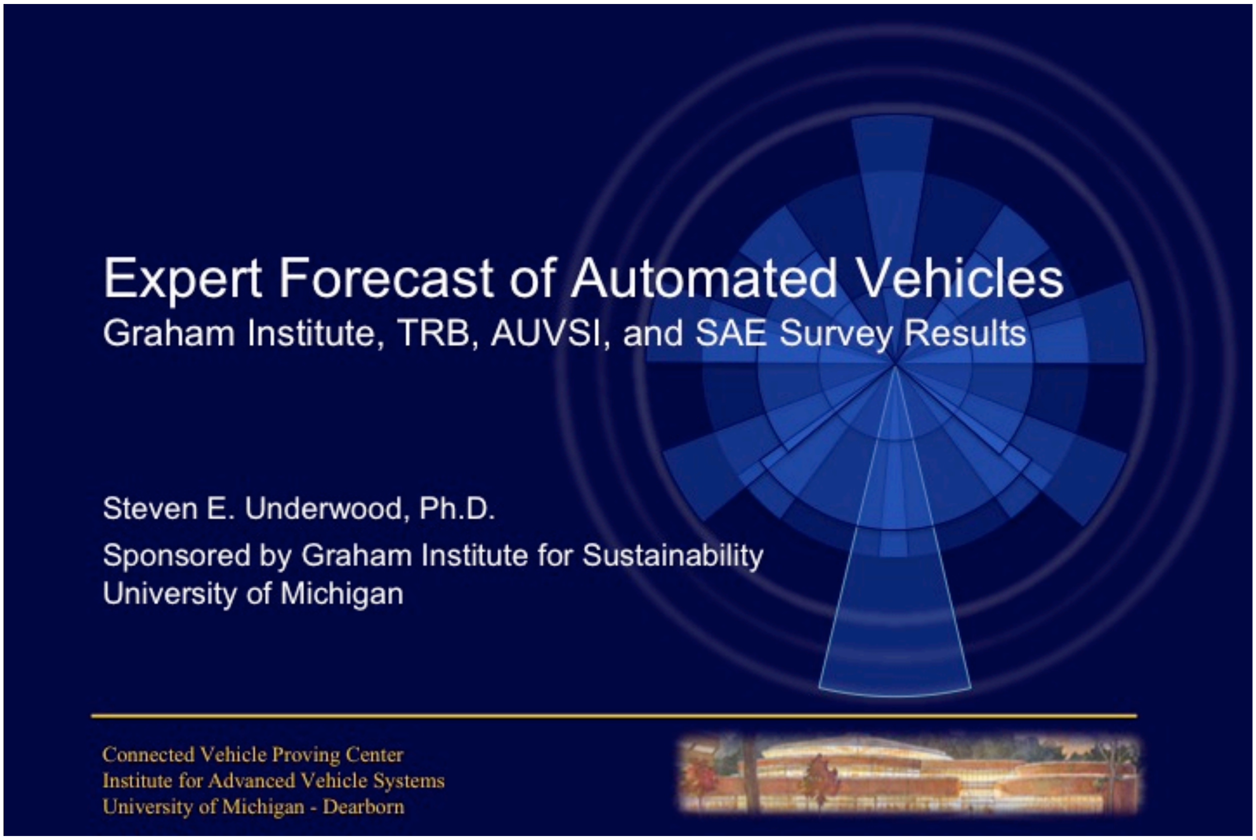
Acronyms

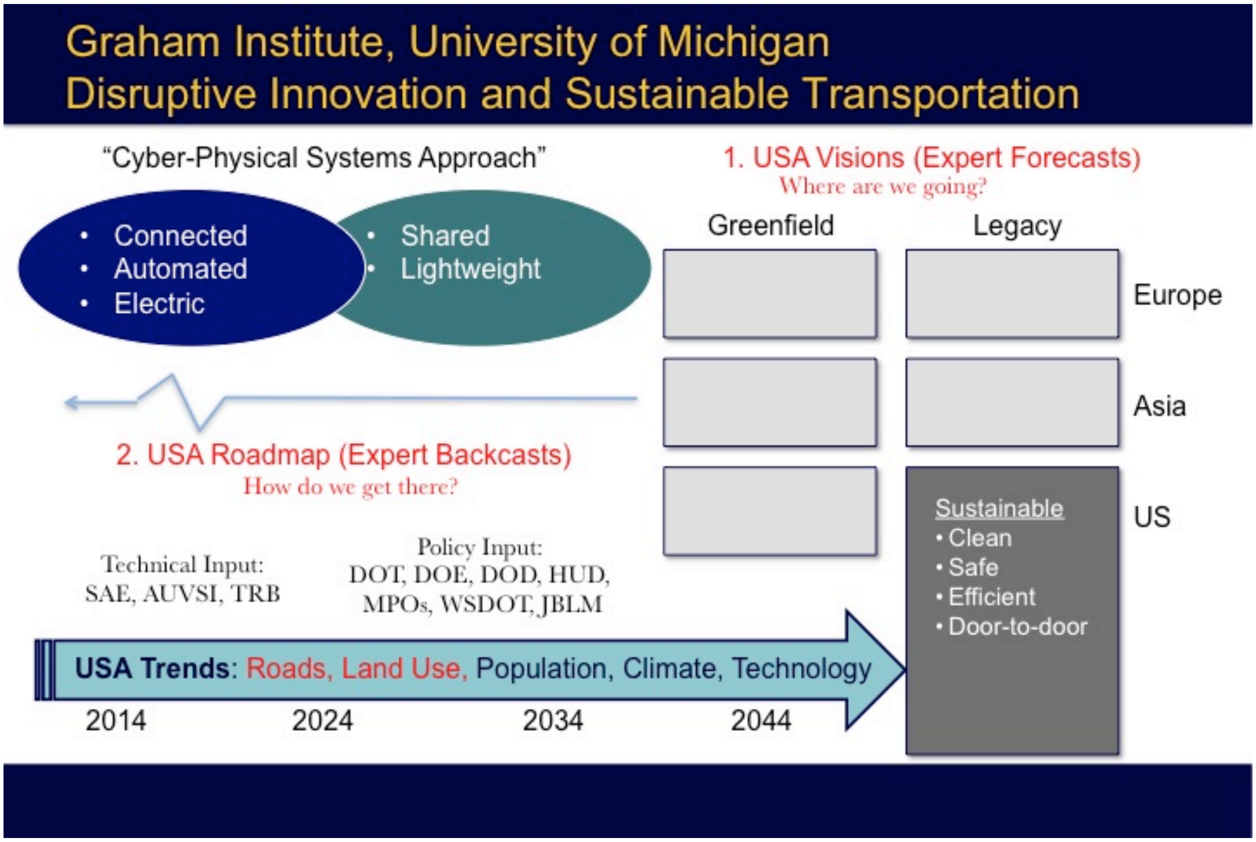
3G	3rd generation GSM
4G	4th generation GSM
ABS	Anti-lock Braking System
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
ADL	Architecture Description Language
AID	Automated Incident Detection
AMAS	Autonomous Mobility Applique System
APD	Avalanche Photodiodes
CACC	Cooperative Adaptive Cruise Control
CIB	Collision Intervention Braking
CMbB	Collision Mitigation by Braking
CPU	Central Processing Unit
DGPS	Differential Global Positioning System
DSP	Digital Signal Processing
DSRC	Dedicated Short Range Communication
ECU	Electronic/Engine Control Unit
ESC	Electronic Stability Control
FOT	Field Operational Test
FOV	Field of View
GNSS	Global Navigation Satellite System
GPRS	Data communication via GSM (General Packet Radio Services)
GPS	Global Positioning System
GPS	Global Positioning System
HIL	Hardware In the Loop
HMI	Human Machine Interface
HUD	Head -Up Display
LCA	Lane Centering Assist
LDW	Lane Departure Warning
LED	Light-Emitting Diode
LIDAR	Light Detection And Ranging

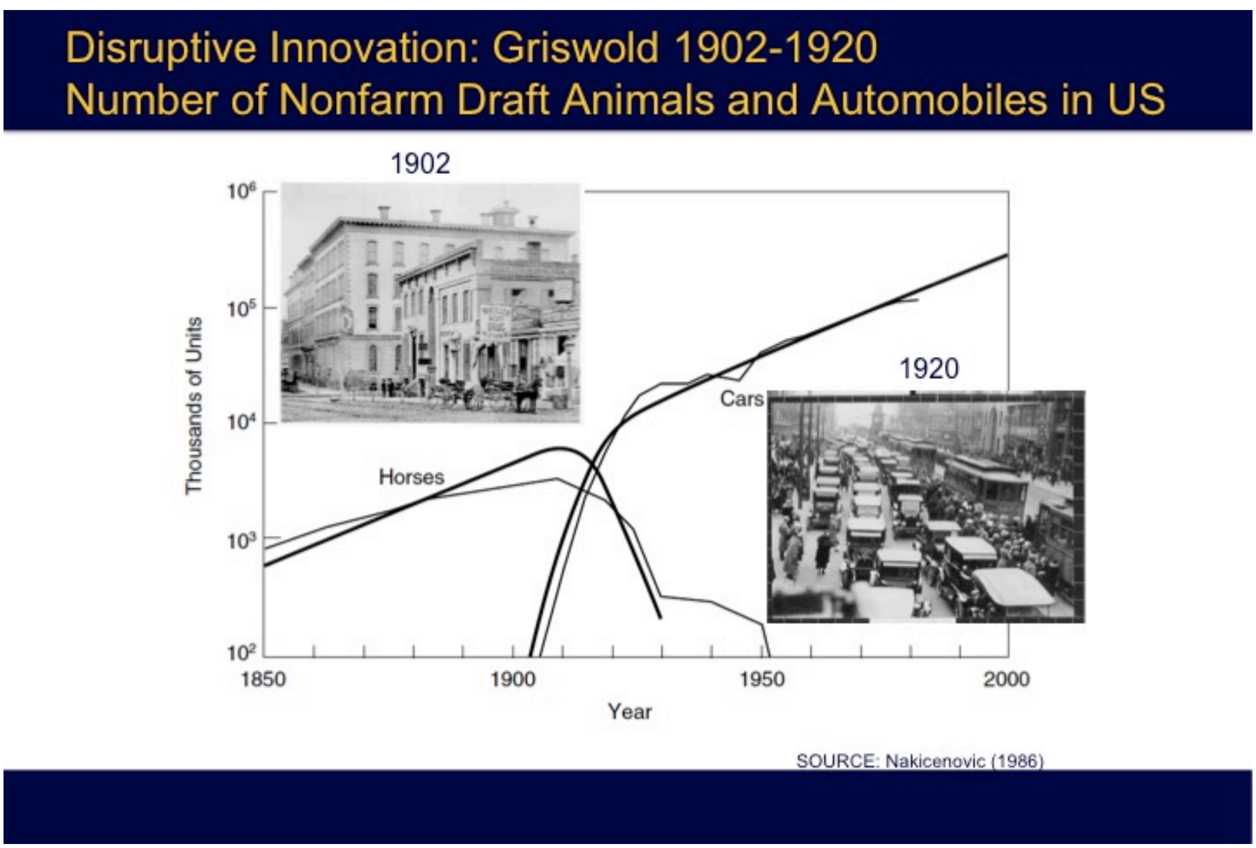
LKAS	Lane Keeping Assist
LTE	Long Term Evolution, 4th generation cellular
MCU	Micro Controller Units
NHTSA	National Highway Traffic and Safety Administration
OEM	Original Equipment Manufacturer
PMT	Photomultipliers
PRIS	Parking Route Information System
R&D	Research and Development
RADAR	Radio Assisted Detection and Ranging
RDS	Radio Data System
RFID	Radio Frequency Identification
RTOS	Real Time Operating Systems
SAE	Society of Automotive Engineers
SIL	Safety Integrity Level
SiPM	Silicon Photomultiplier
SLAM	Simultaneous Localization and Mapping
Tier 1 supplier	A supplier who directly delivers to OEM companies
TJA	Traffic Jam Assist
TMC	Traffic Message Channel
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to- other road user/infrastructure or X (cloud)

Appendix A. Presentation Summary

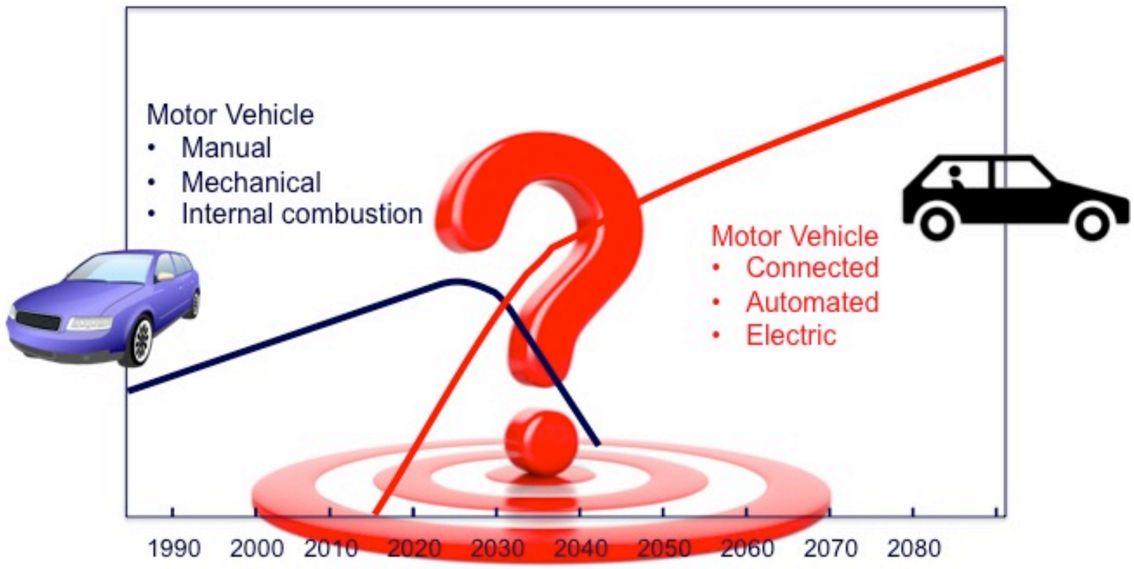
This appendix contains a set of slides from my presentation of results from the expert survey. This material was presented and a visit to the US Department of Transportation, the Automated Vehicle Symposium sponsored by held in San Francisco, July 15 through17, 2014, and the SAE Convergence Conference in Detroit in October, 2014.



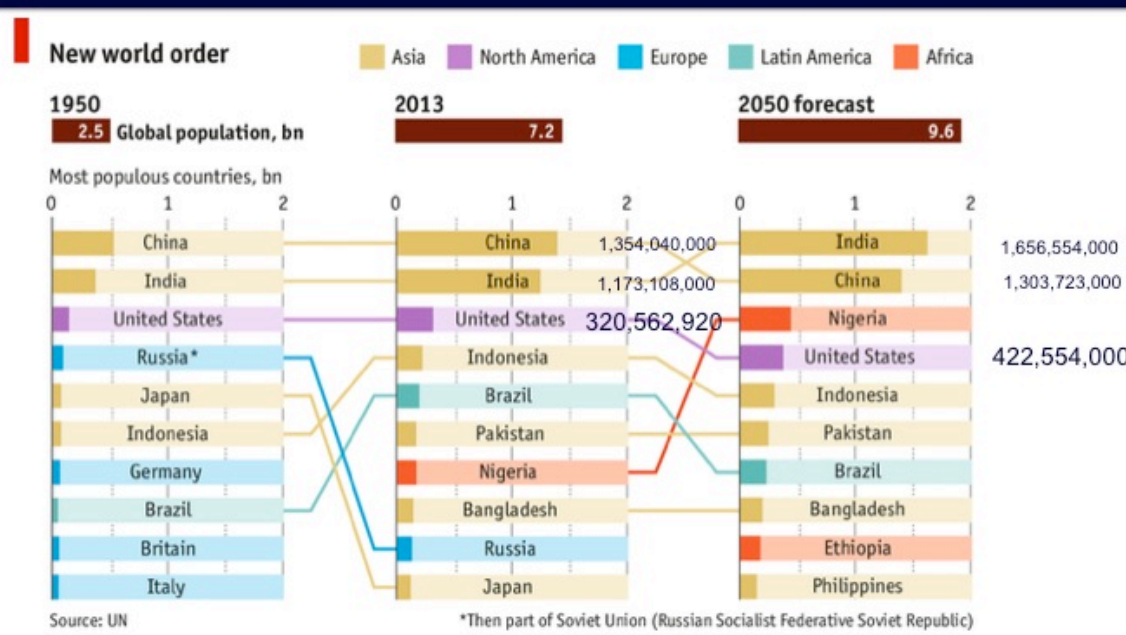

Graham Institute, University of Michigan
Disruptive Innovation and Sustainable Transportation
"Cyber-Physical Systems Approach"
Connected
Automated
Electric
Shared
Lightweight
1. USA Visions (Expert Forecasts)
Where are we going?
Greenfield
Legacy
Europe
Asia
US
Sustainable
Clean
Safe
Efficient
Door-to-door
2. USA Roadmap (Expert Backcasts)
How do we get there?
Technical Input:
SAE, AUVSI, TRB
Policy Input:
DOT, DOE, DOD, HUD,
MPOs, WSDOT, JBLM
USA Trends: Roads, Land Use, Population, Climate, Technology
2014
2024
2034
2044


Disruptive Innovation: Griswold 1902-1920
Number of Nonfarm Draft Animals and Automobiles in US
1902
1920
Thousands of Units
10^6
10^5
10^4
10^3
10^2
Horses
Cars
1850
1900
1950
2000
Year
SOURCE: Nakicenovic (1986)

Disruptive Innovation?

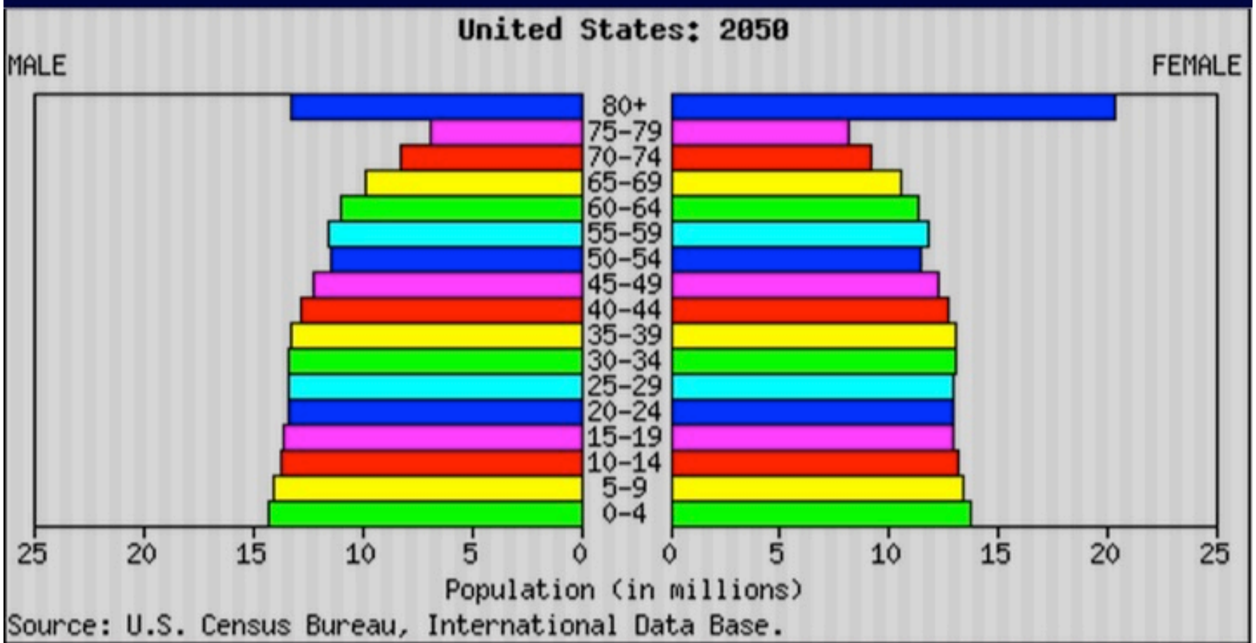


Background Population Forecast by Country

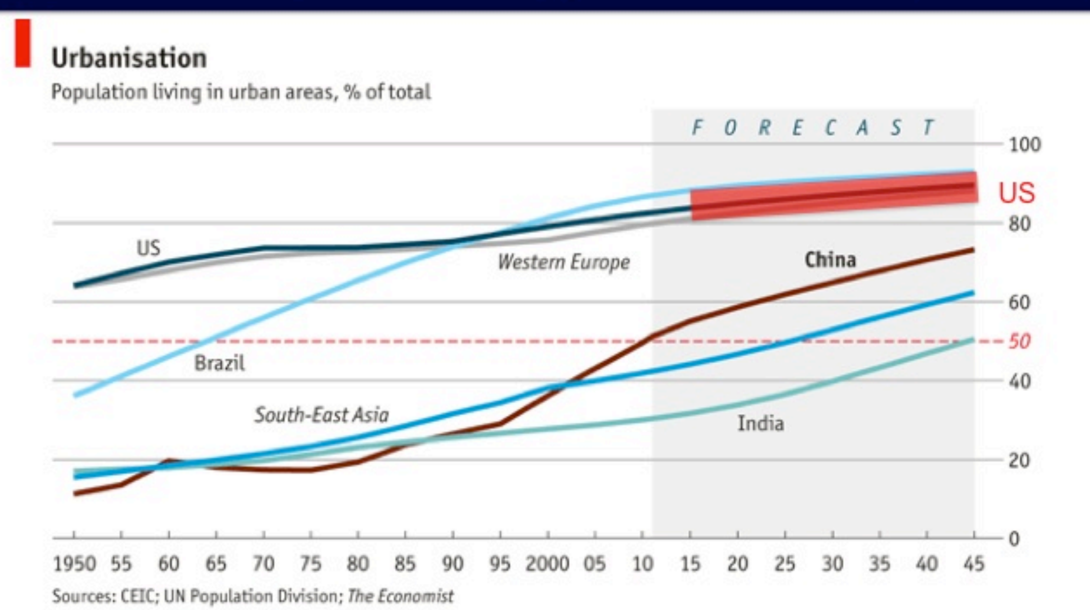


International Data Base (IDB) Division of the United States Census Bureau

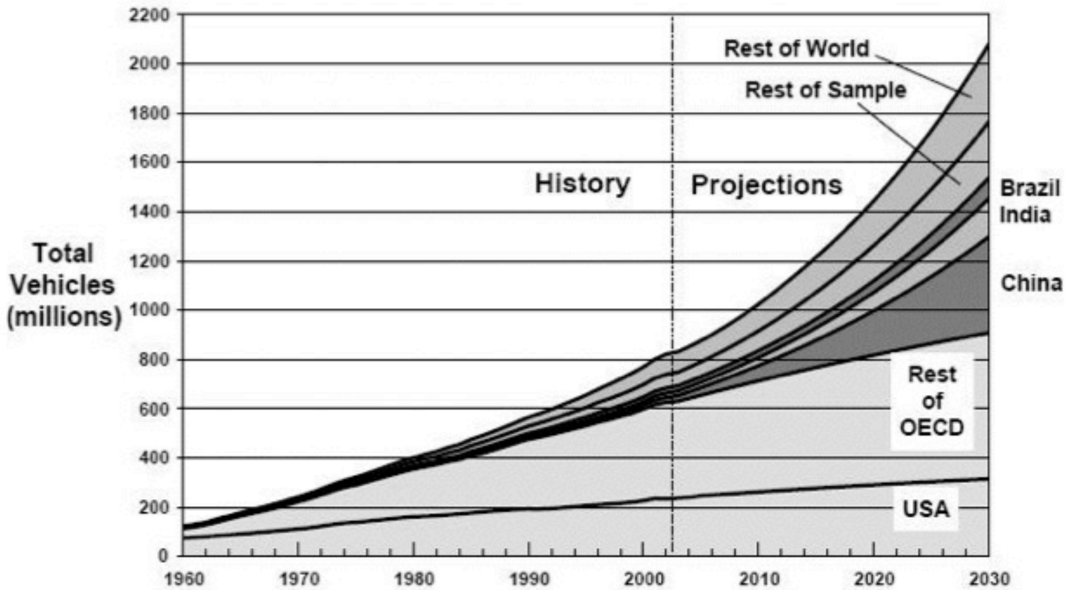
USA Population Projection 2050



Urbanization: Population Living in Urban Areas (% of total)

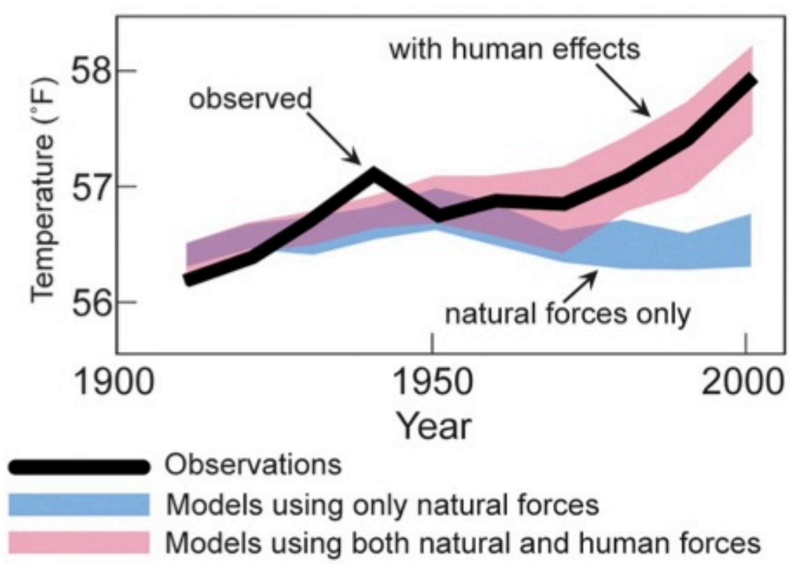


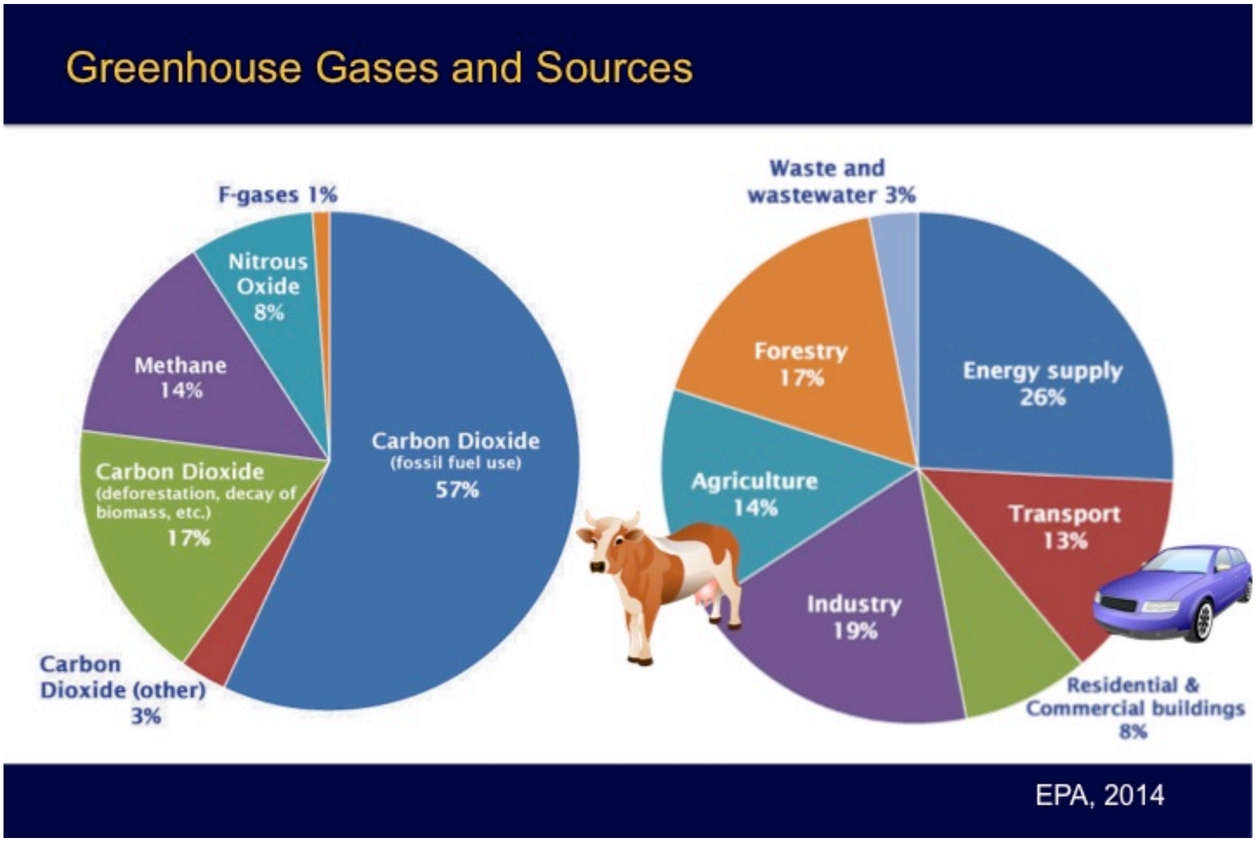
Total Vehicles by Country Forecast

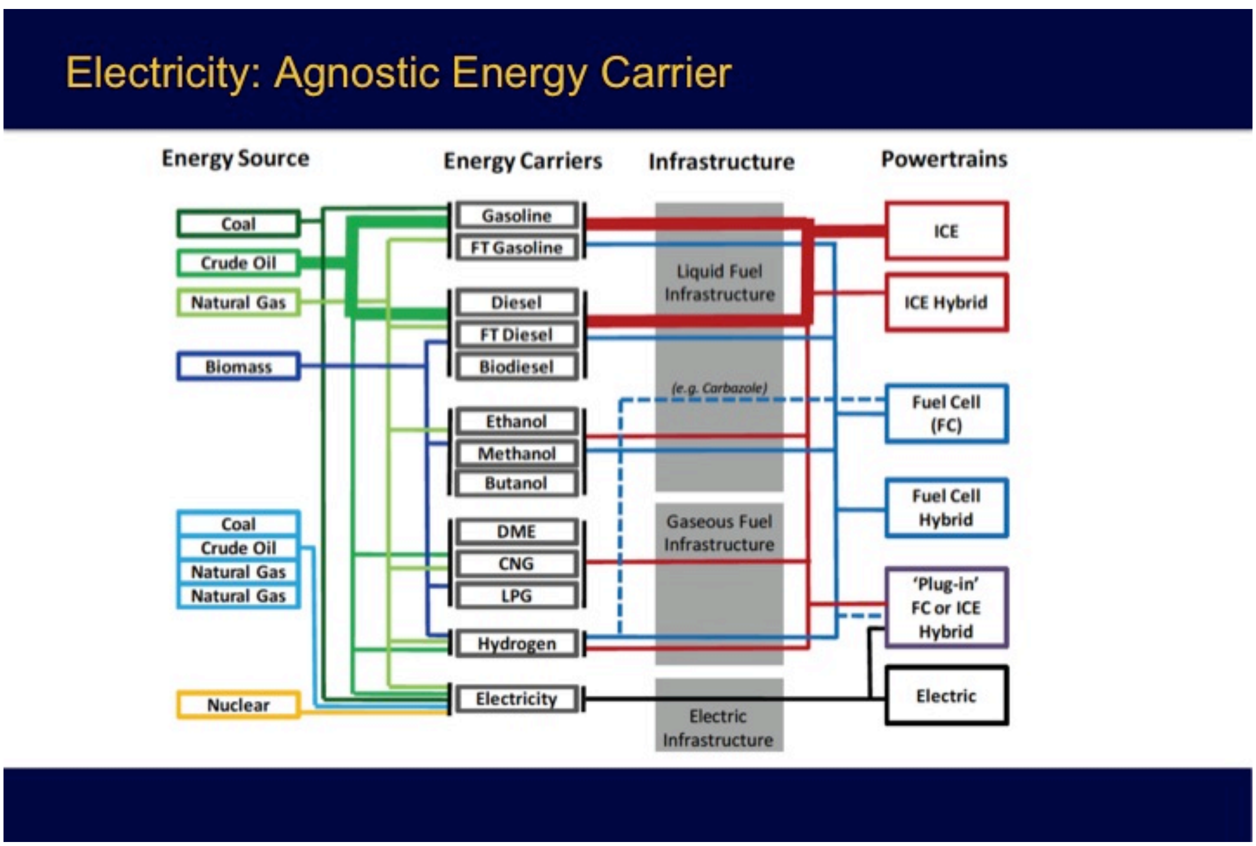


Dave Cohen

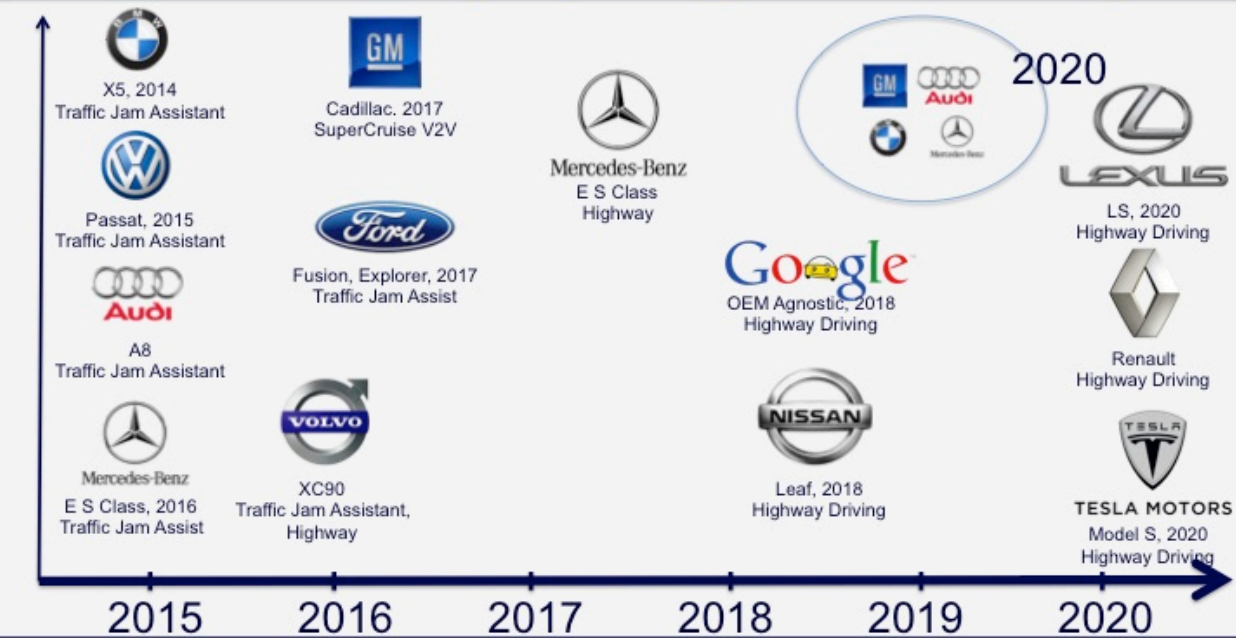
Human Effects on Warming




Greenhouse Gases and Sources
F-gases 1%
Nitrous Oxide 8%
Methane 14%
Carbon Dioxide (deforestation, decay of biomass, etc.) 17%
Carbon Dioxide (fossil fuel use) 57%
Carbon Dioxide (other) 3%
Waste and wastewater 3%
Forestry 17%
Energy supply 26%
Agriculture 14%
Transport 13%
Industry 19%
Residential & Commercial buildings 8%
EPA, 2014


Electricity: Agnostic Energy Carrier
Energy Source
Energy Carriers
Infrastructure
Powertrains
Coal
Crude Oil
Natural Gas
Biomass
Coal
Crude Oil
Natural Gas
Natural Gas
Nuclear
Gasoline
FT Gasoline
Diesel
FT Diesel
Biodiesel
Ethanol
Methanol
Butanol
DME
CNG
LPG
Hydrogen
Electricity
Liquid Fuel Infrastructure
(e.g. Carbazole)
Gaseous Fuel Infrastructure
Electric Infrastructure
ICE
ICE Hybrid
Fuel Cell (FC)
Fuel Cell Hybrid
'Plug-in' FC or ICE Hybrid
Electric

Press Releases:
Traffic Jam Assist, Highway Driving, Automated Parking



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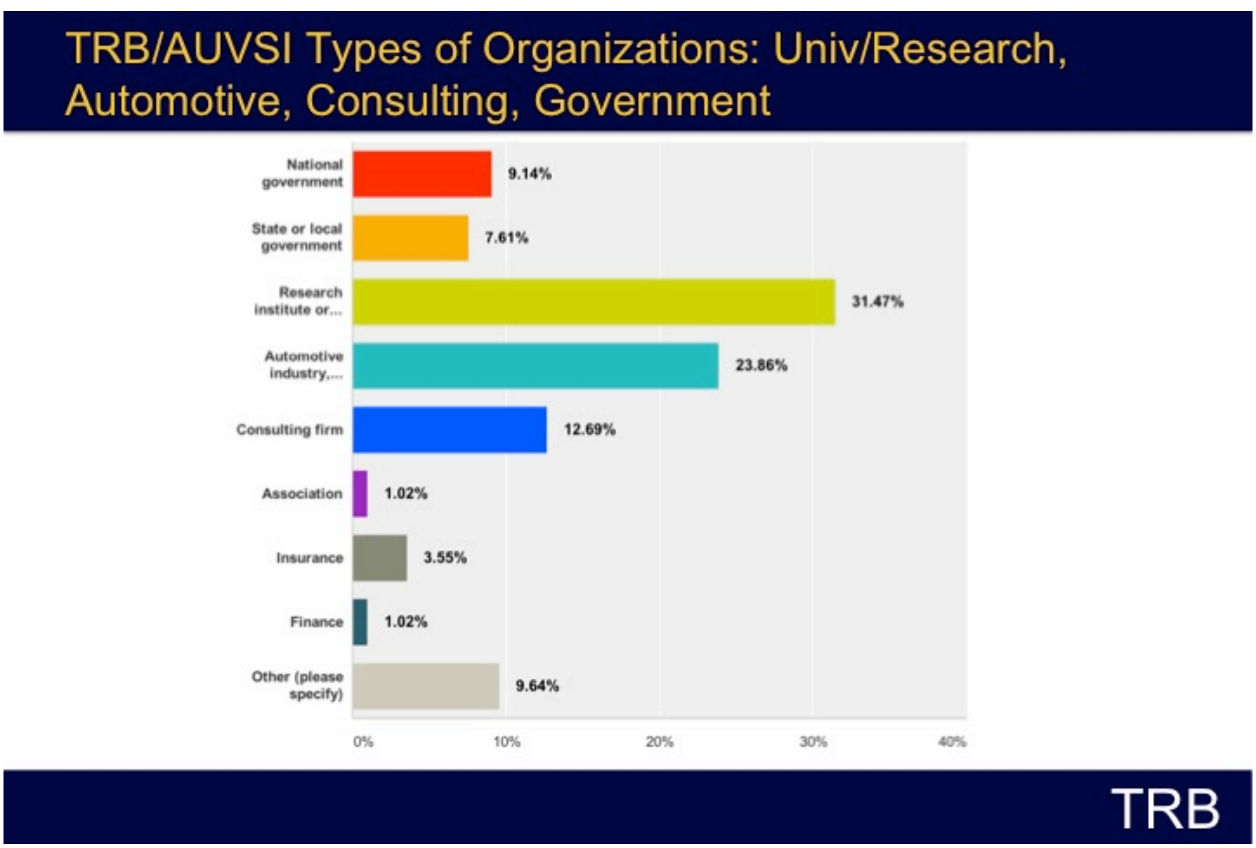
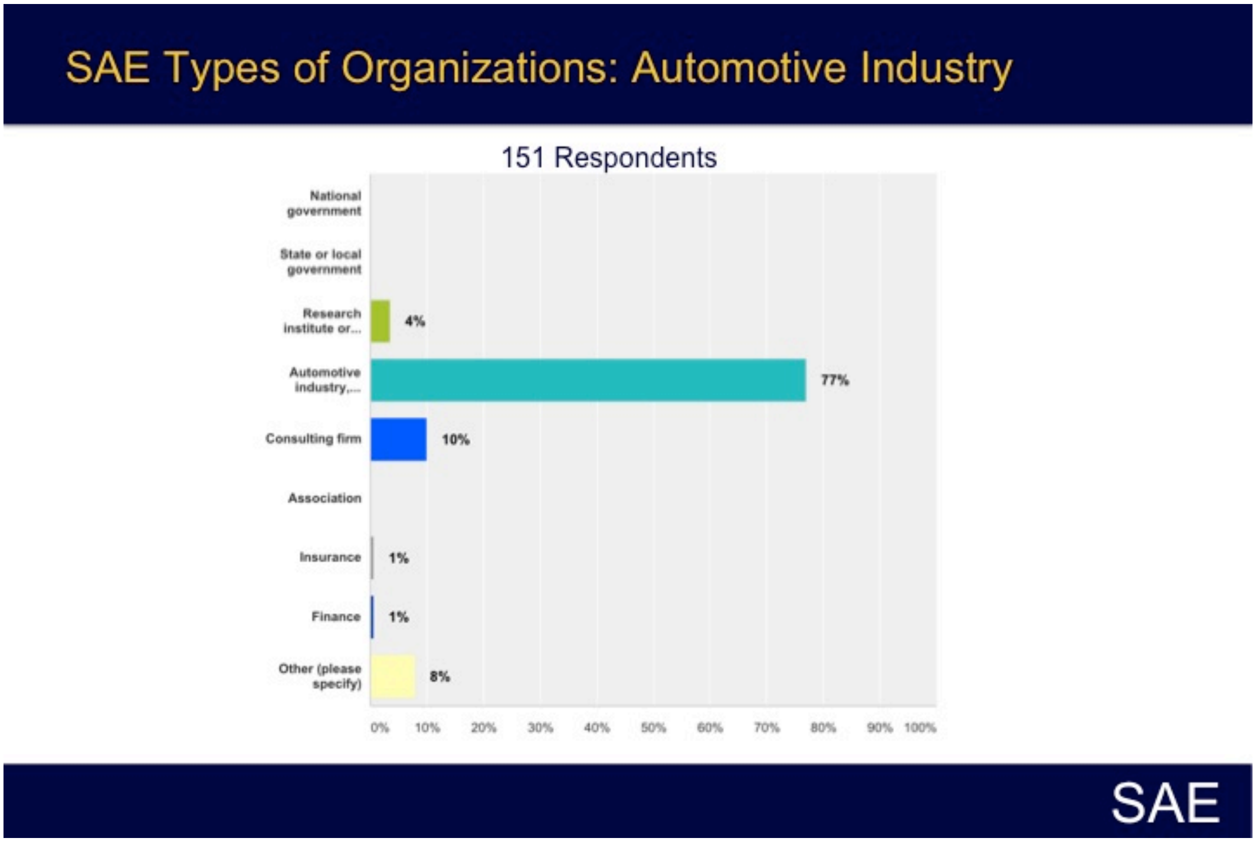
12

Three Surveys

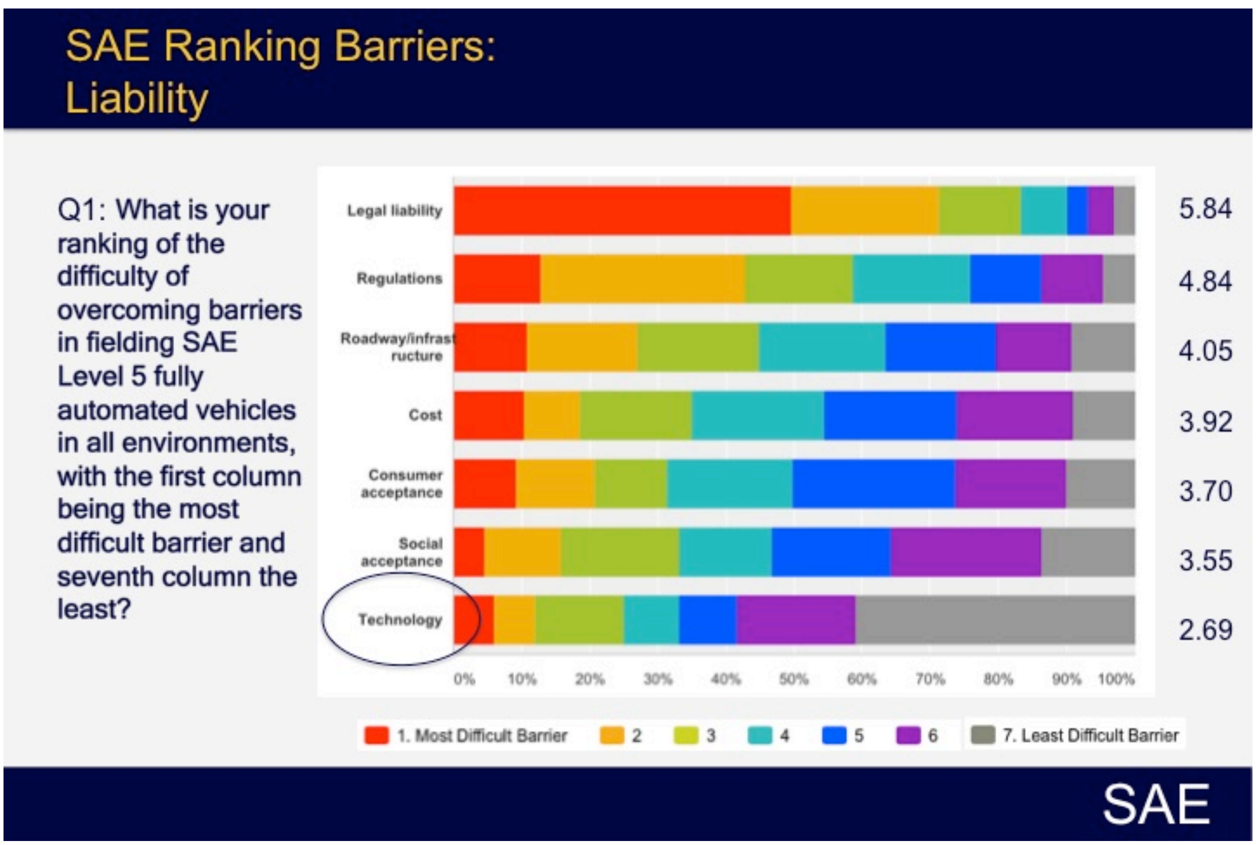
- Graham Institute, Expert Panel, 20 expert panelists
- TRB/AUVSI Symposium, 250 attendees responded
- SAE Convergence, 151 attendees responded

SAE Level	SAE Name	SAE Narrative Definition	Execution of Steering/ Acceleration/ Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task	System capability (driving modes)
	Human Driver monitors the driving environment					
0	No Automation	Warnings, Driver Information … *driver* of … even when enhanced by warning or intervention	Human Driver	Human Driver	Human Driver	N/A
1	Driver Assistance	Adaptive Cruise Control, (braking accel) Lane Keeping (steering) Lane Centering (steering), ABS, ESC … that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human Driver and Systems	Human Driver	Human Driver	Some Driving Modes
2	Partial Automation	Traffic Jam Assist, (braking, acceleration, & steering) … one or more … ring and … ation about … expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human Driver	Human Driver	Some Driving Modes
	Automated driving system ("system") monitors the driving environment					
3	Conditional Automation	Freeway Driving … ic performance by an … m of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human Driver	Some Driving Modes
4	High Automation	Freeway Pilot, Campus Shuttle Freight Platooning, Urban Automation	System	System	**System**	Some Driving Modes
5	Full Automation	Robotic Taxi … mance by an *automated driving* … cts of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	**System**	Some Driving Modes





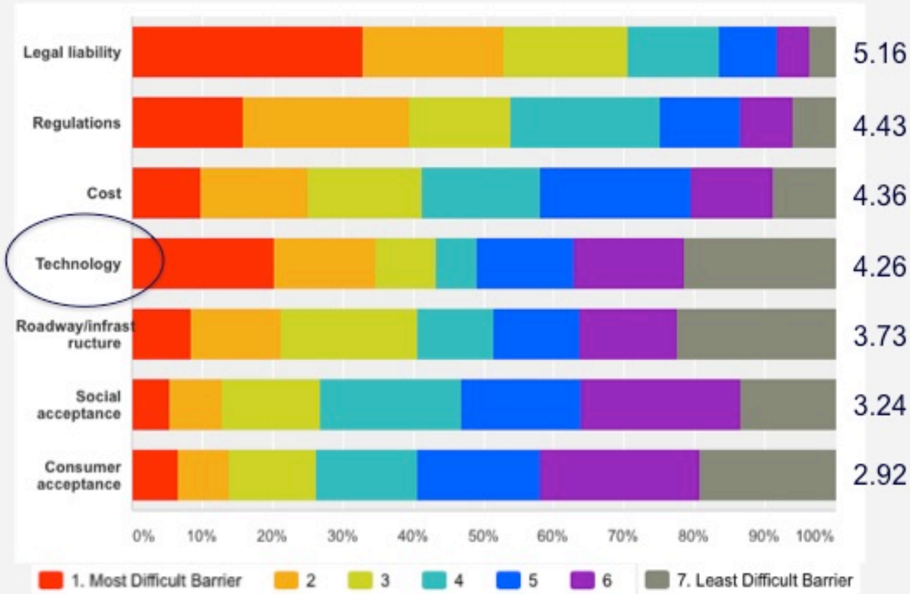
SAE Types of Organizations: Automotive Industry
151 Respondents
National government
State or local government
Research institute or...
4%
Automotive industry,...
77%
Consulting firm
10%
Association
Insurance
1%
Finance
1%
Other (please specify)
8%
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
SAE



SAE Ranking Barriers: Liability
Q1: What is your ranking of the difficulty of overcoming barriers in fielding SAE Level 5 fully automated vehicles in all environments, with the first column being the most difficult barrier and seventh column the least?
Legal liability
5.84
Regulations
4.84
Roadway/infrastructure
4.05
Cost
3.92
Consumer acceptance
3.70
Social acceptance
3.55
Technology
2.69
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
1. Most Difficult Barrier
2
3
4
5
6
7. Least Difficult Barrier
SAE

TRB Ranking Barriers:
Liability, Regulations, Cost, Technology

Q1: What is your ranking of the difficulty of overcoming barriers in fielding SAE Level 5 fully automated vehicles in all environments, with the first column being the most difficult barrier and seventh column the least?



SAE Ranking Barriers:
Liability

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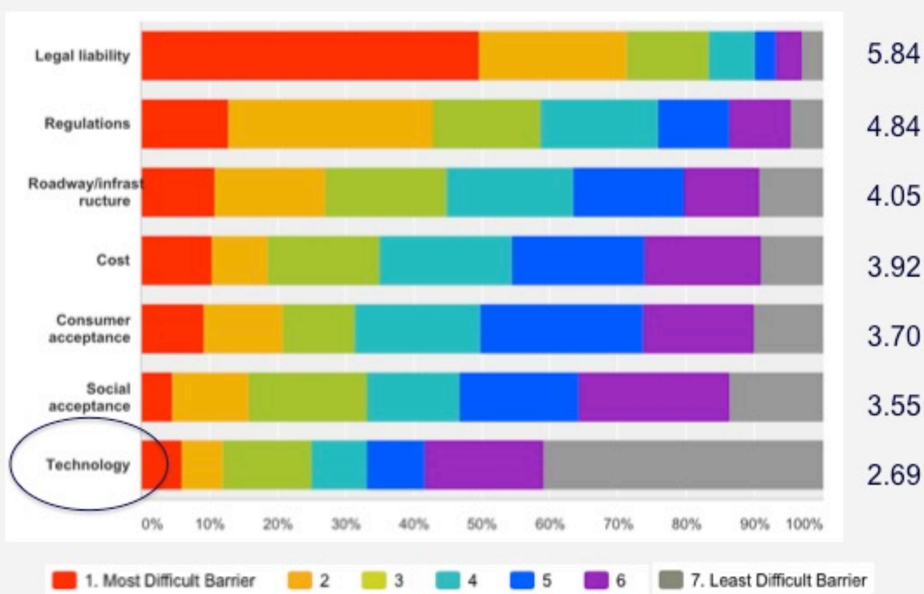
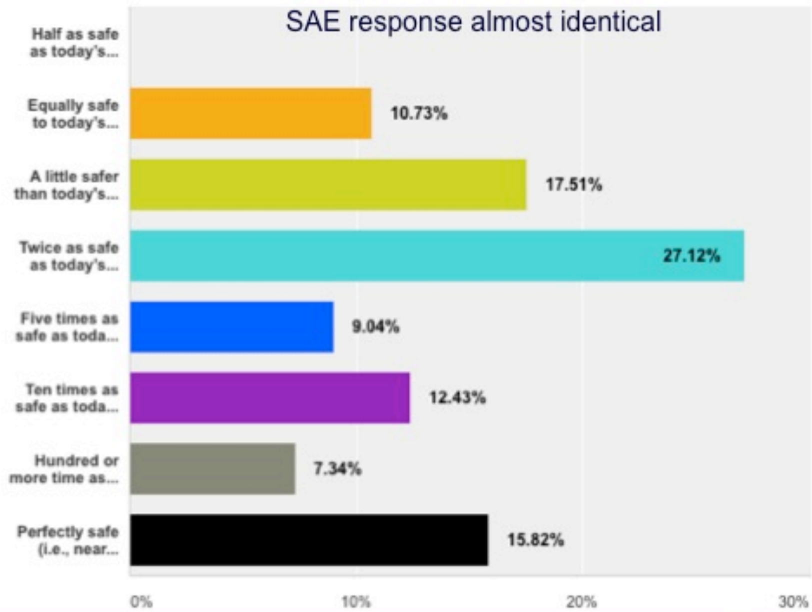


SAE

TRB Required Level of Safety: Little Safer to Very Safe

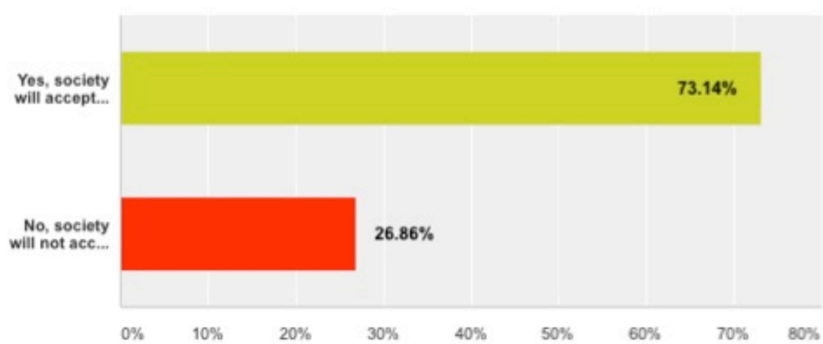
Q2: What level of safety do you believe an automated driving system (at any level of automation) should be required to demonstrate before it is authorized for public use?



TRB

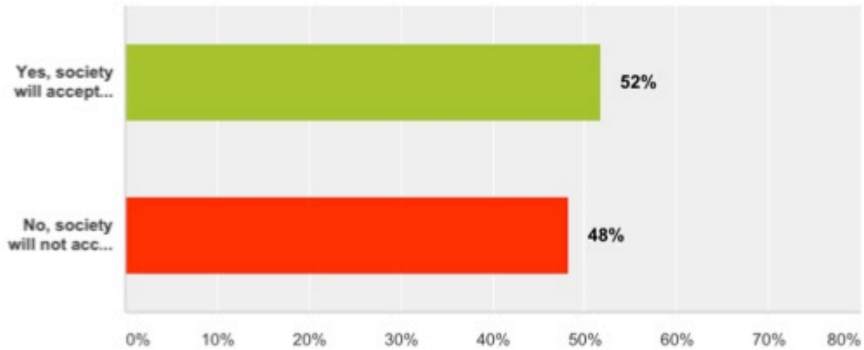
TRB Accept Automated Vehicles Causing Crashes

Q3: If automated vehicles result in a significant reduction in road accidents and fatalities, will society accept that automated vehicles occasionally cause some of the remaining accidents and fatalities?



SAE Accept Automated Vehicles Causing Crashes

Q3: If automated vehicles result in a significant reduction in road accidents and fatalities, will society accept that automated vehicles occasionally cause some of the remaining accidents and fatalities?

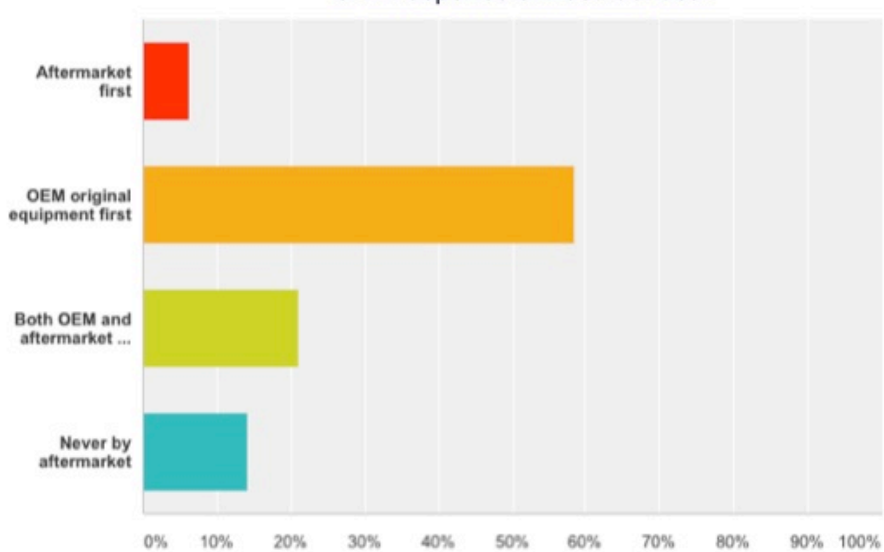


SAE

TRB First Sales: OEM?

Q4: Do you expect automated driving systems (SAE Level 3 or above) to be first sold to the general public as after-market retrofits to existing vehicles, or as original equipment on new vehicles, or both?

SAE response almost identical

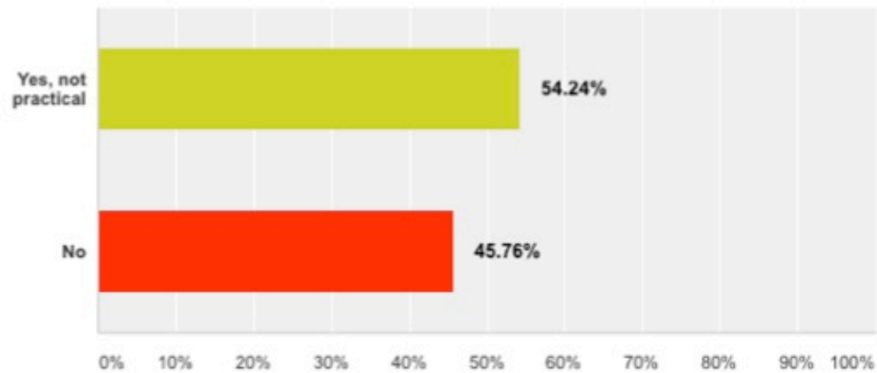


TRB

TRB, Conditional Automation (Level 3) Not Practical?

Q5: Is SAE Level 3 conditional automation, in which the driver is expected to intervene quickly if needed, not practical or safe because drivers are likely to become complacent with automated operation and not behave as required?

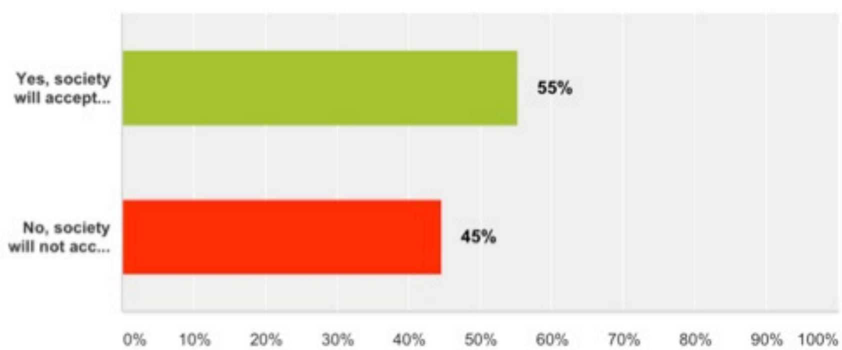
SAE response almost identical



TRB

TRB, V2V Necessary for SAE Level 5?

Q6: Do you believe that vehicle-to-vehicle communication will be necessary for fully automated SAE Level 5 operation, to extend the sensing horizon to other vehicles or to improve the availability of information about the other vehicles?



TRB

SAE, V2V Necessary for SAE Level 5?

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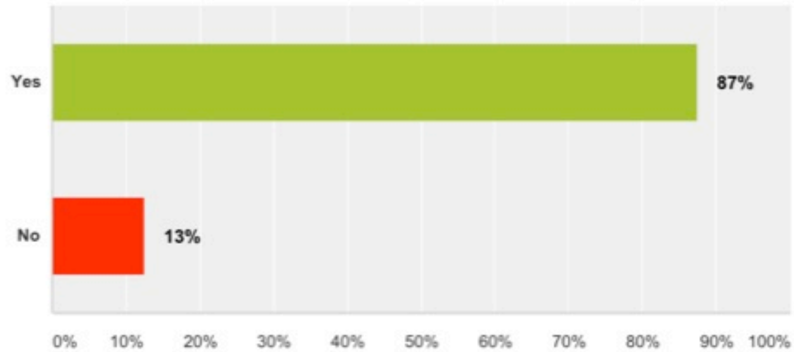
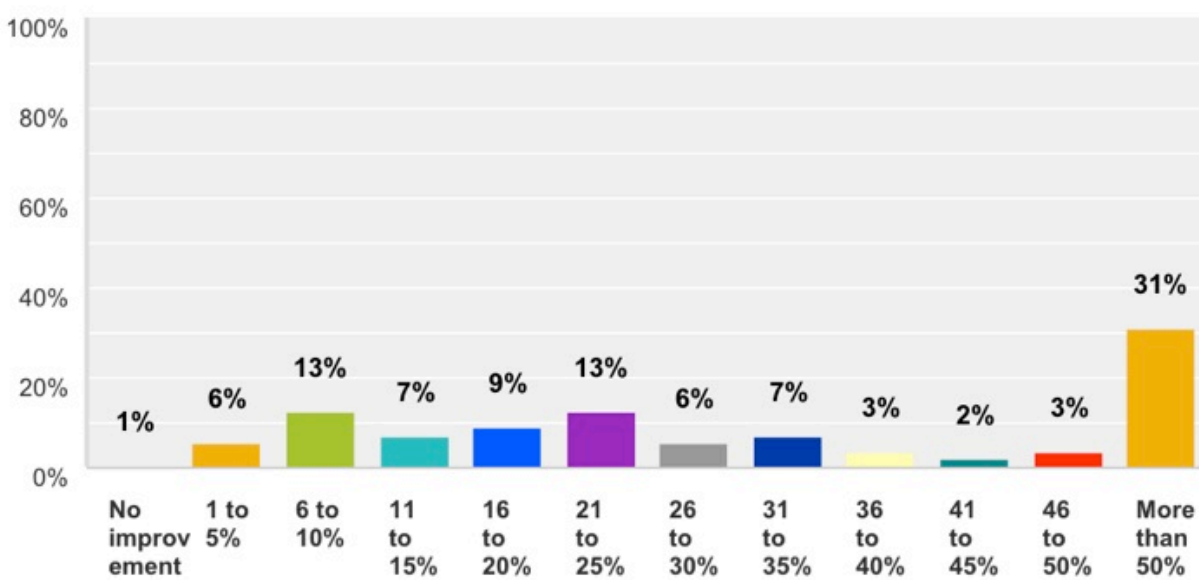


SAE

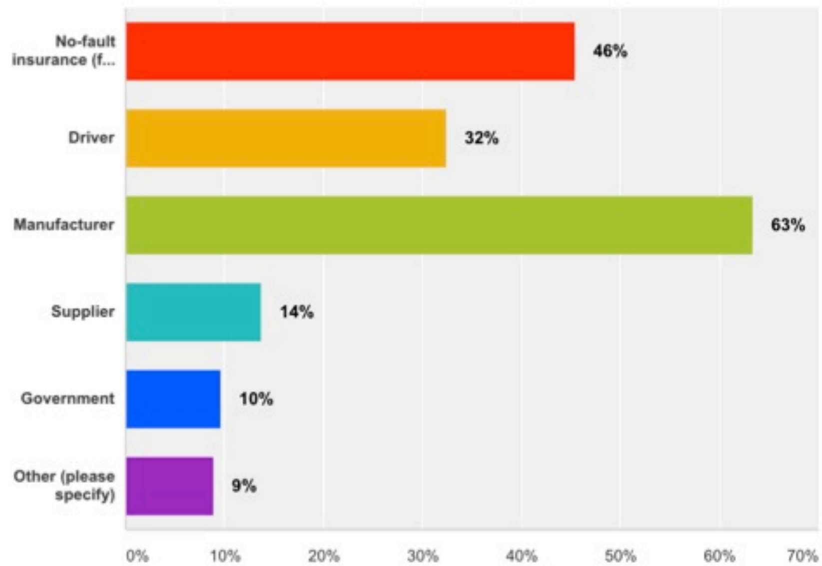
SAE, Percentage Reduction in Traffic Fatalities 2013-2025



SAE

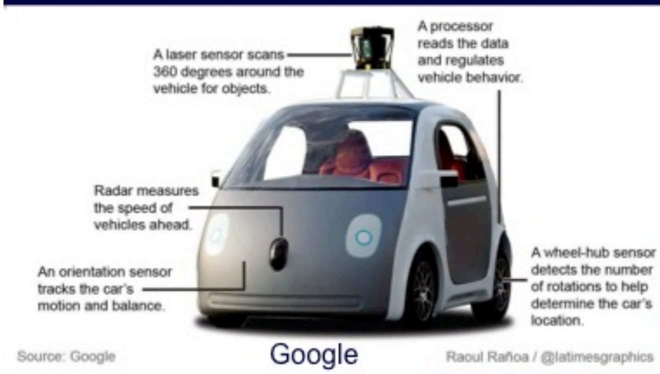
Liability and Responsibliies for Crashes In Automated Mode

It is speculated that the more advanced automated vehicle systems will enable to driver to disengage from the driving task (e.g., feet off the pedals, hands off the steering wheel, and eyes off the road) and attend to other activities in the vehicle (e.g., communicating on smart devices) while relying on the automated vehicle systems to perform the driving tasks in complete safety and even in the case of electrical or other failure it will fail safely. In case of system failure and a crash with such a high level of automation who do you believe will accept responsibility and liability in most cases while the automated vehicle system is engaged and driving the vehicle? (Select multiple of you believe the responsiblity/liablity will be shared)



SAE

Automated Shuttle



Automated Shuttle, SAE Level 4 (Q22), Graham, TRB

- Low-speed, short distance, fully automated,
- On "campus" or roadway with limited vehicle and pedestrian traffic.
- Operator or passenger intervention may be required in unusual circumstances (e.g., animal will not move off the path).
- The vehicle is designed to fail safely if a problem occurs

1st Quartile	Median	3rd Quartile
2015	2016	2017
2016	2018	2020

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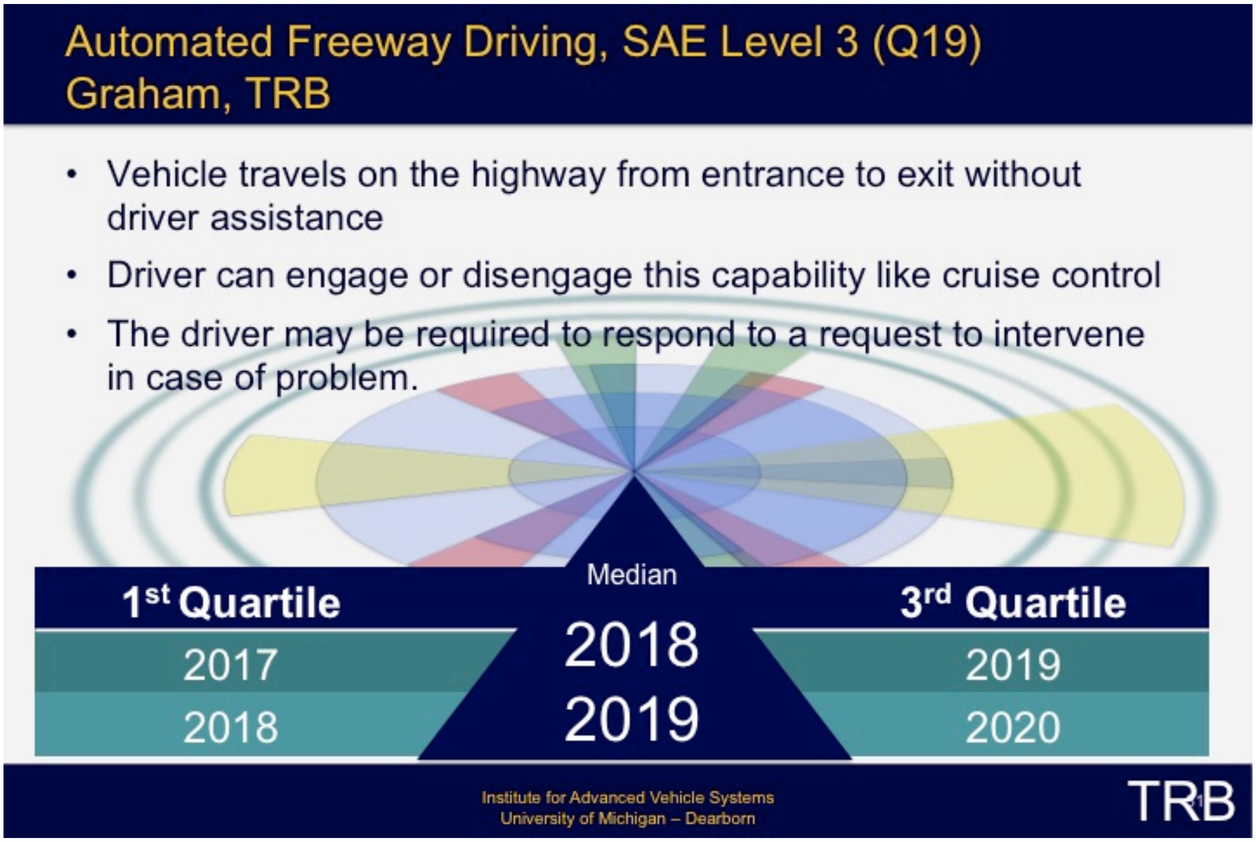
TRB

Automated Freeway Driving


Automated Freeway Driving, SAE Level 3 (Q19)
Graham, TRB
• Vehicle travels on the highway from entrance to exit without driver assistance
• Driver can engage or disengage this capability like cruise control
• The driver may be required to respond to a request to intervene in case of problem.
1st Quartile
2017
2018
Median
2018
2019
3rd Quartile
2019
2020
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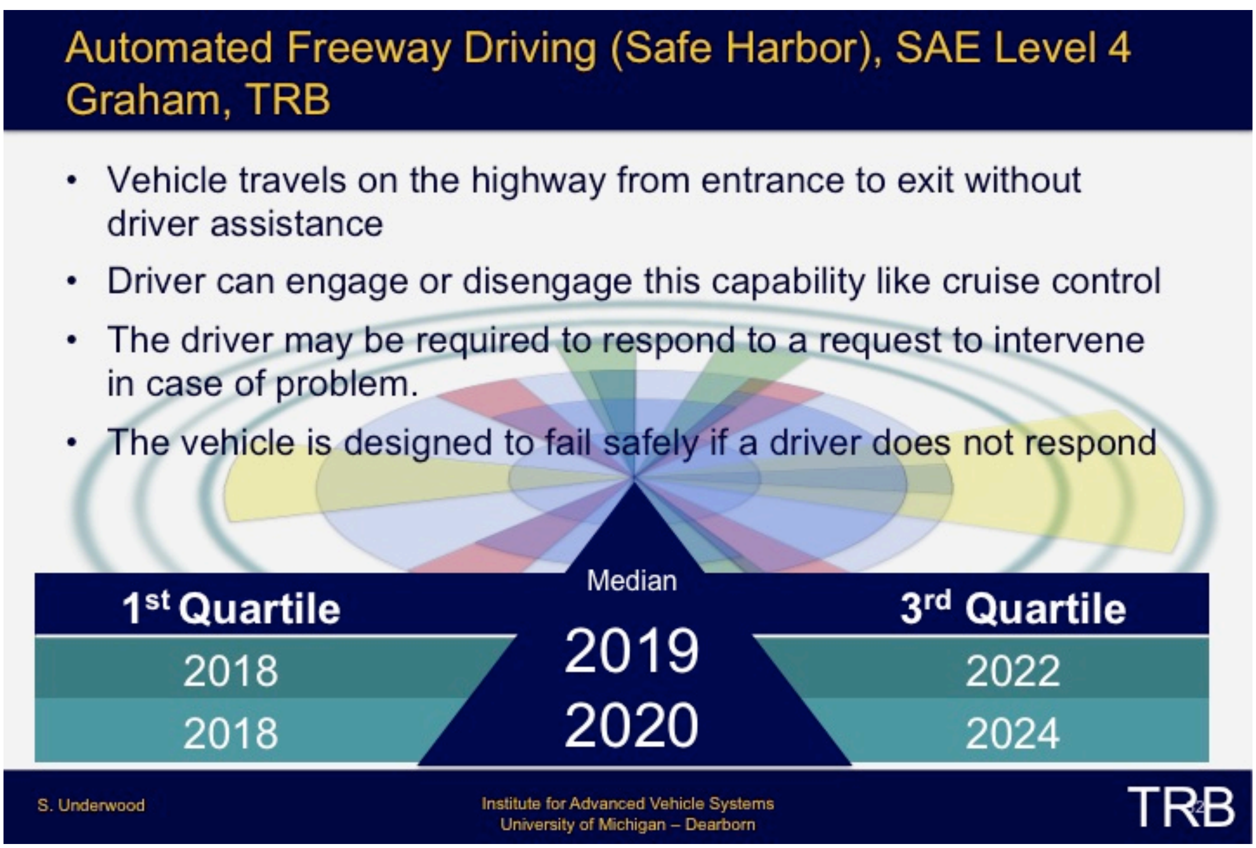
Automated Freeway Driving (Safe Harbor), SAE Level 4
Graham, TRB
• Vehicle travels on the highway from entrance to exit without driver assistance
• Driver can engage or disengage this capability like cruise control
• The driver may be required to respond to a request to intervene in case of problem.
• The vehicle is designed to fail safely if a driver does not respond
1st Quartile
2018
2018
Median
2019
2020
3rd Quartile
2022
2024
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TRB

Truck Platooning

Automated Freight Platooning, SAE Level 4 (Q21) Graham, TRB

- Cooperative adaptive cruise control and automated steering
- Short headways to reduce wind resistance Drivers in all trucks.
- Driver may be required to respond to request to intervene in case of problem.
- This may or may not involve a dedicated lane.
- The vehicle is designed to fail safely if a driver does not respond

1st Quartile	Median	3rd Quartile
2019	2020	2022
2019	2020	2024

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TRB

High Automation, SAE Level 4 (Q23) Graham, TRB

- Vehicle is in control from beginning to end of trip both on highway and surface streets, urban and rural, where human driver responds to request to intervene.
- The vehicle is designed to fail safely if the driver does not respond

1st Quartile	Median	3rd Quartile
2024	2025	2028
2024	2025	2030

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TRB

Full Automation

Full Automation, SAE Level 5 (Q24)
Graham, TRB

- Vehicle is in control from beginning to end of trip, both on highway and surface streets, urban and rural, without human intervention.
- The vehicle is designed to fail safely if problem occurs. (e.g., automated taxi);

1st Quartile	Median	3rd Quartile
2025	2030	2035
2027	2030	2035

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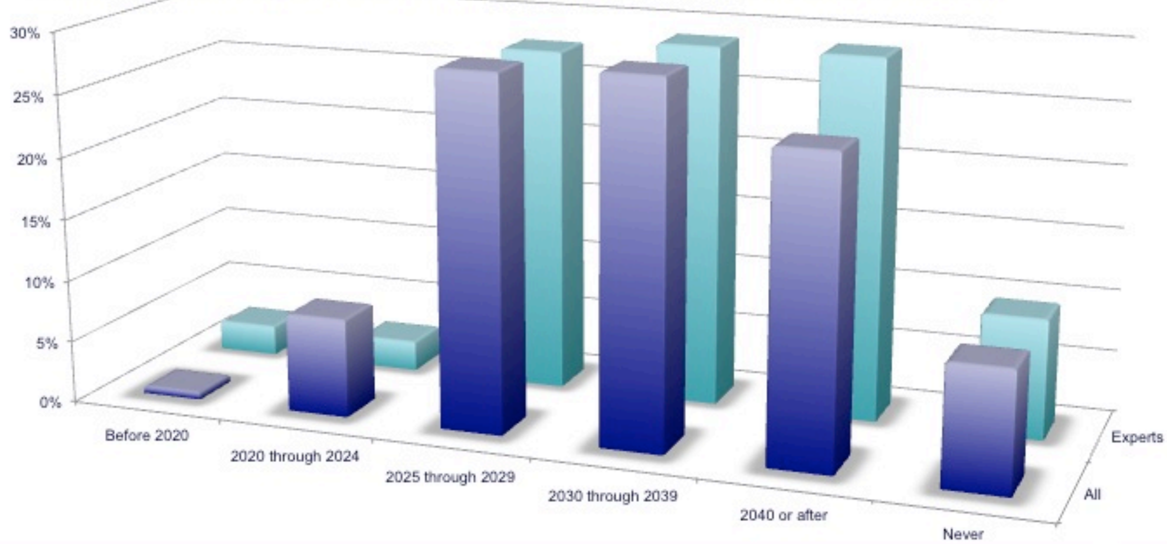
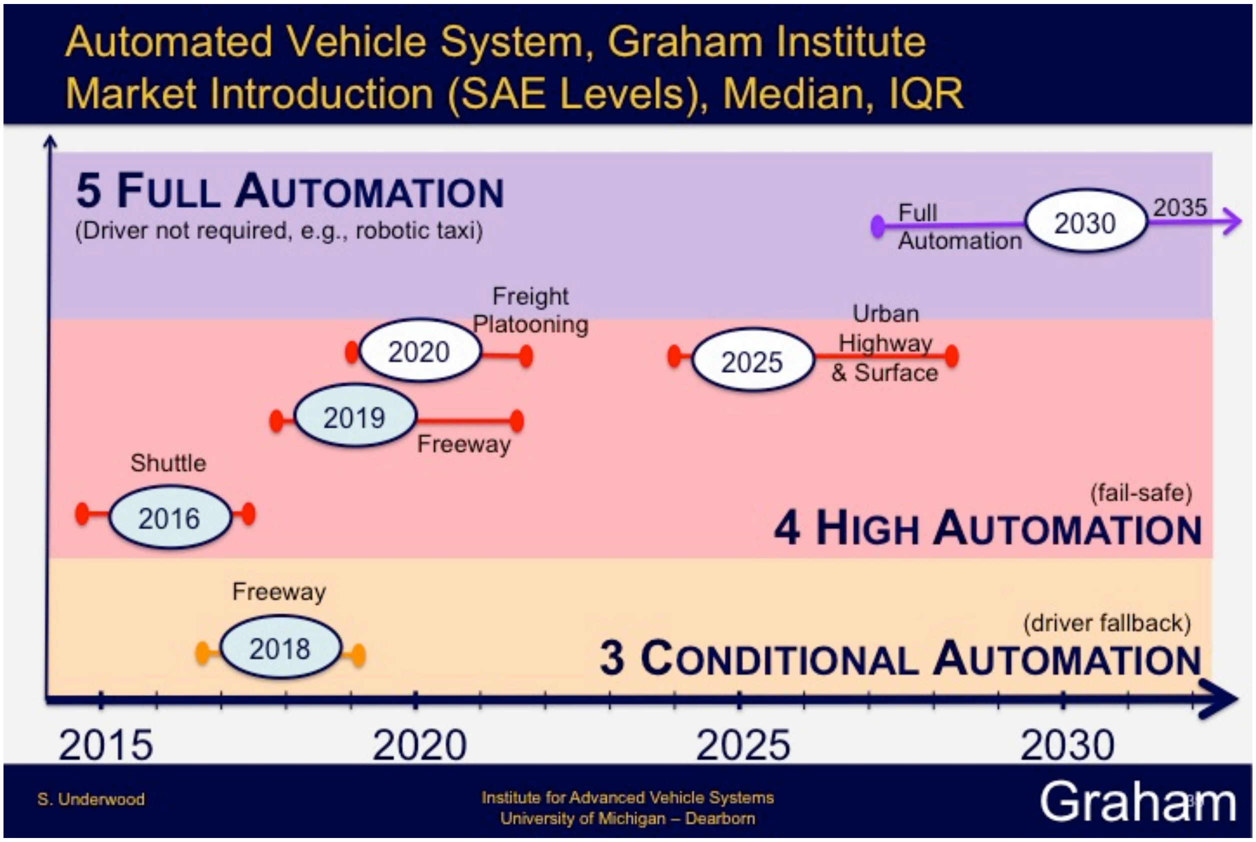
TRB

Kids to School

Q16: When do you expect to be able to trust a fully automated taxi to take your elementary-school-age child or grandchild to their school (with no licensed driver onboard)?



TRB



Automated Vehicle System, Graham Institute
Market Introduction (SAE Levels), Median, IQR
5 FULL AUTOMATION
(Driver not required, e.g., robotic taxi)
Full Automation
2030
2035
Freight Platooning
2020
Urban Highway & Surface
2025
2019
Freeway
Shuttle
2016
(fail-safe)
4 HIGH AUTOMATION
Freeway
2018
(driver fallback)
3 CONDITIONAL AUTOMATION
2015
2020
2025
2030
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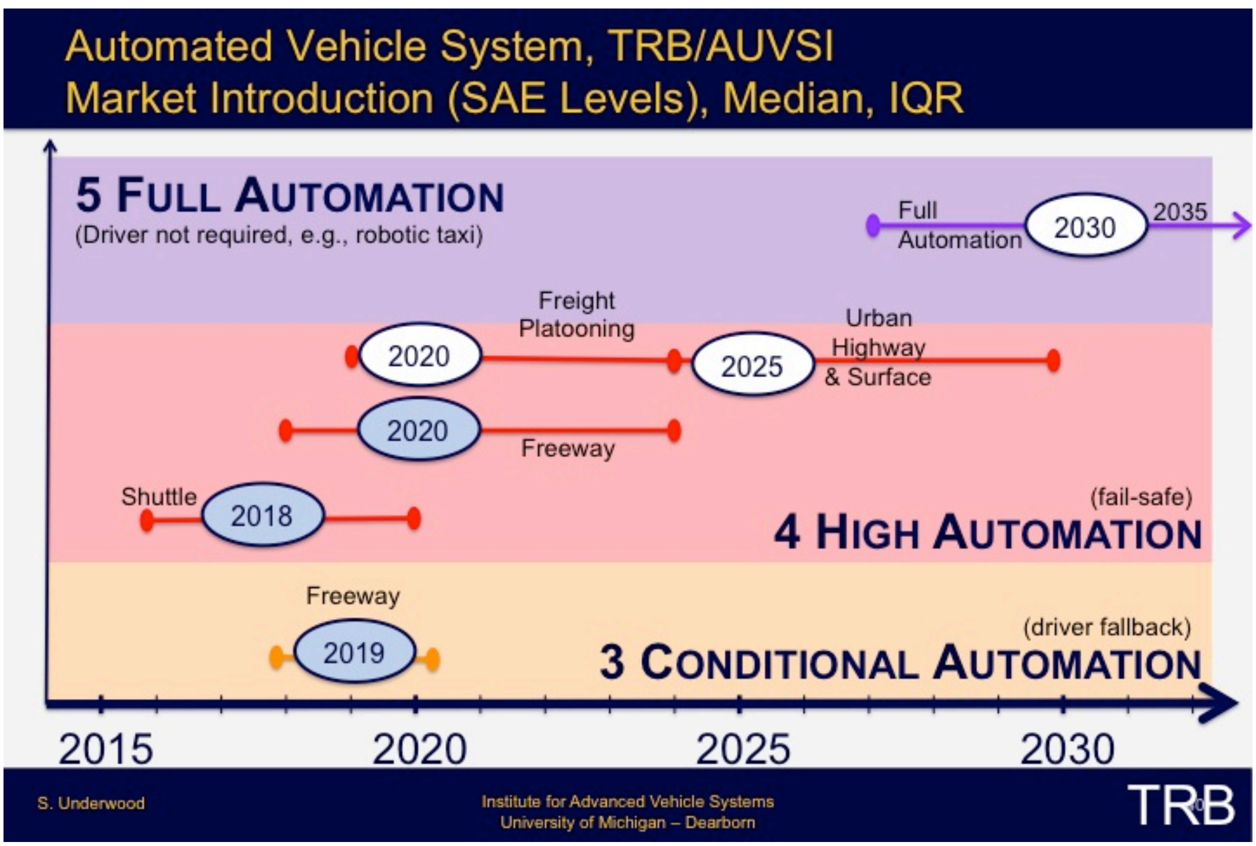
Graham



Automated Vehicle System, TRB/AUVSI
Market Introduction (SAE Levels), Median, IQR
5 FULL AUTOMATION
(Driver not required, e.g., robotic taxi)
Full Automation
2030
2035
Freight Platooning
2020
Urban Highway & Surface
2025
2020
Freeway
Shuttle
2018
(fail-safe)
4 HIGH AUTOMATION
Freeway
2019
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3 CONDITIONAL AUTOMATION
2015
2020
2025
2030
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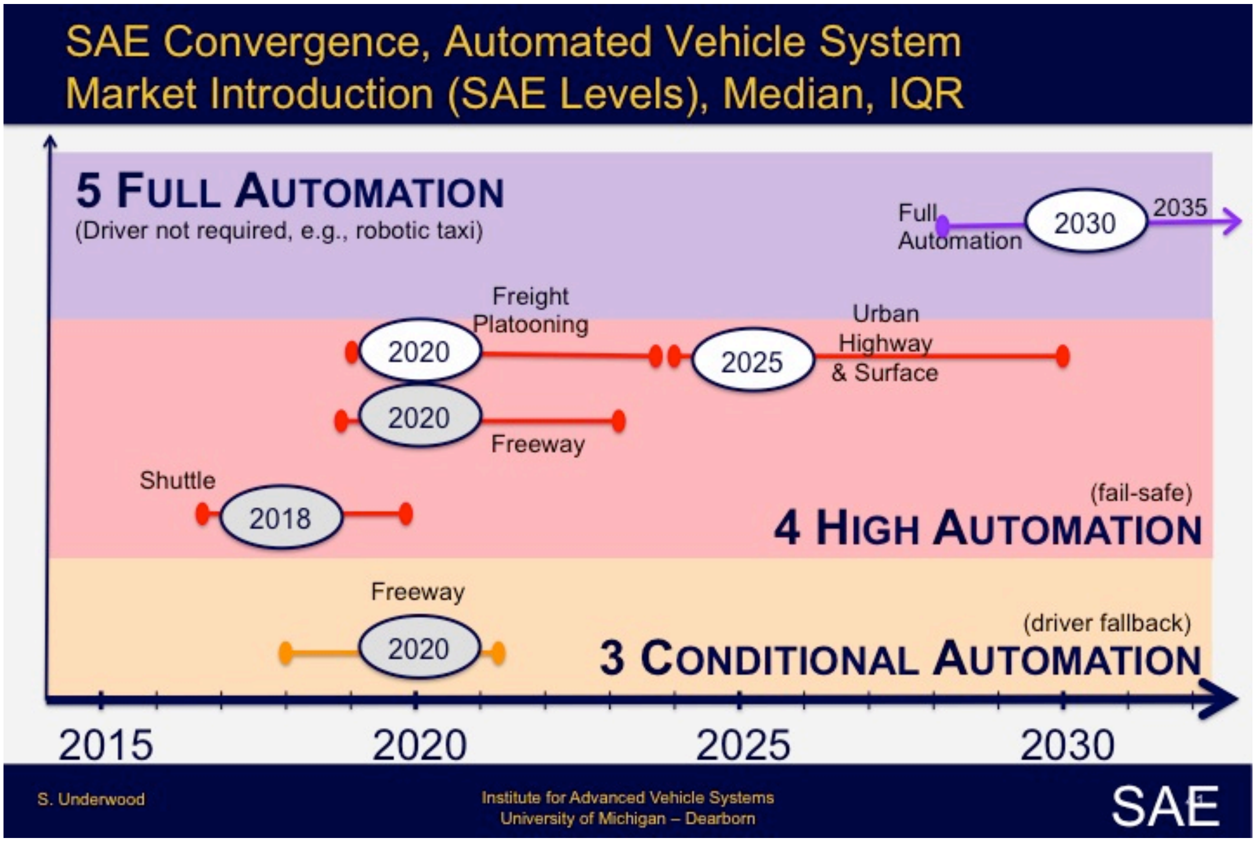
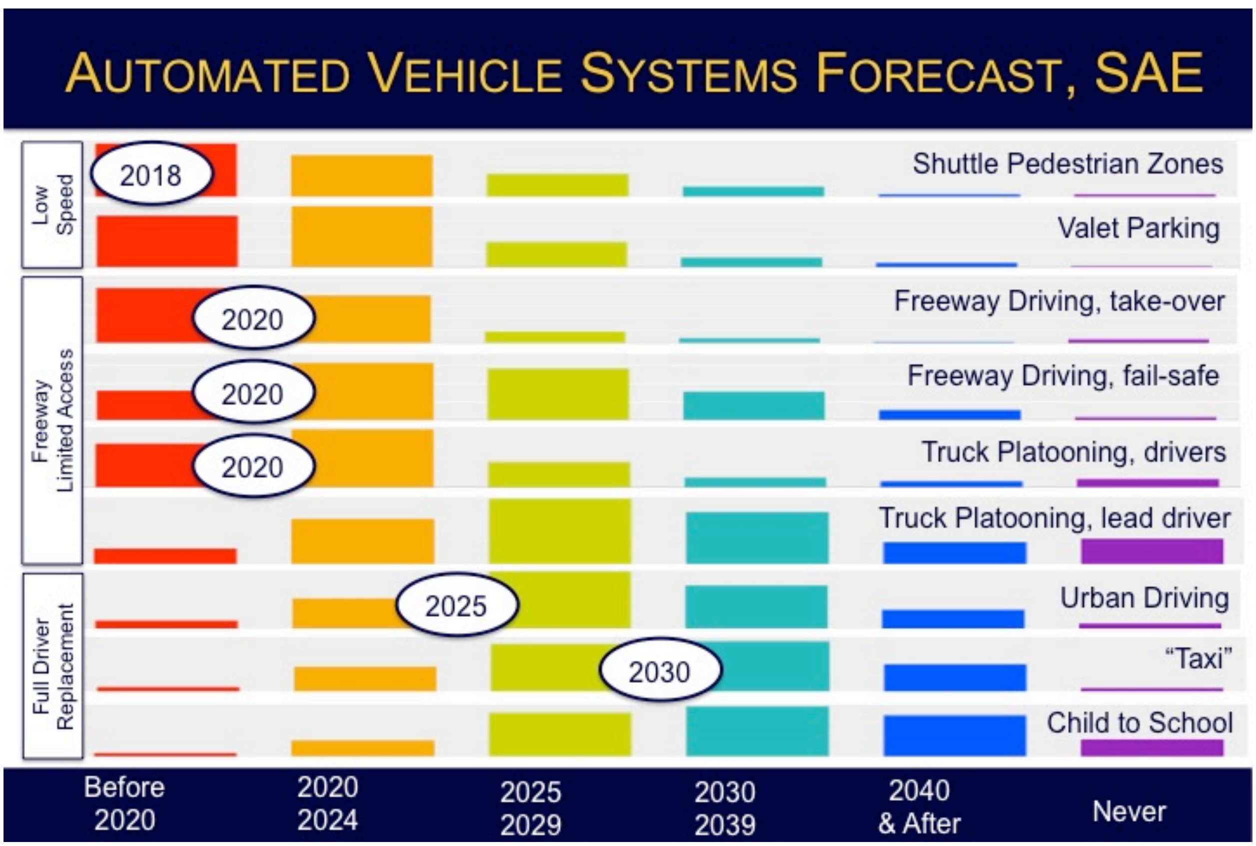
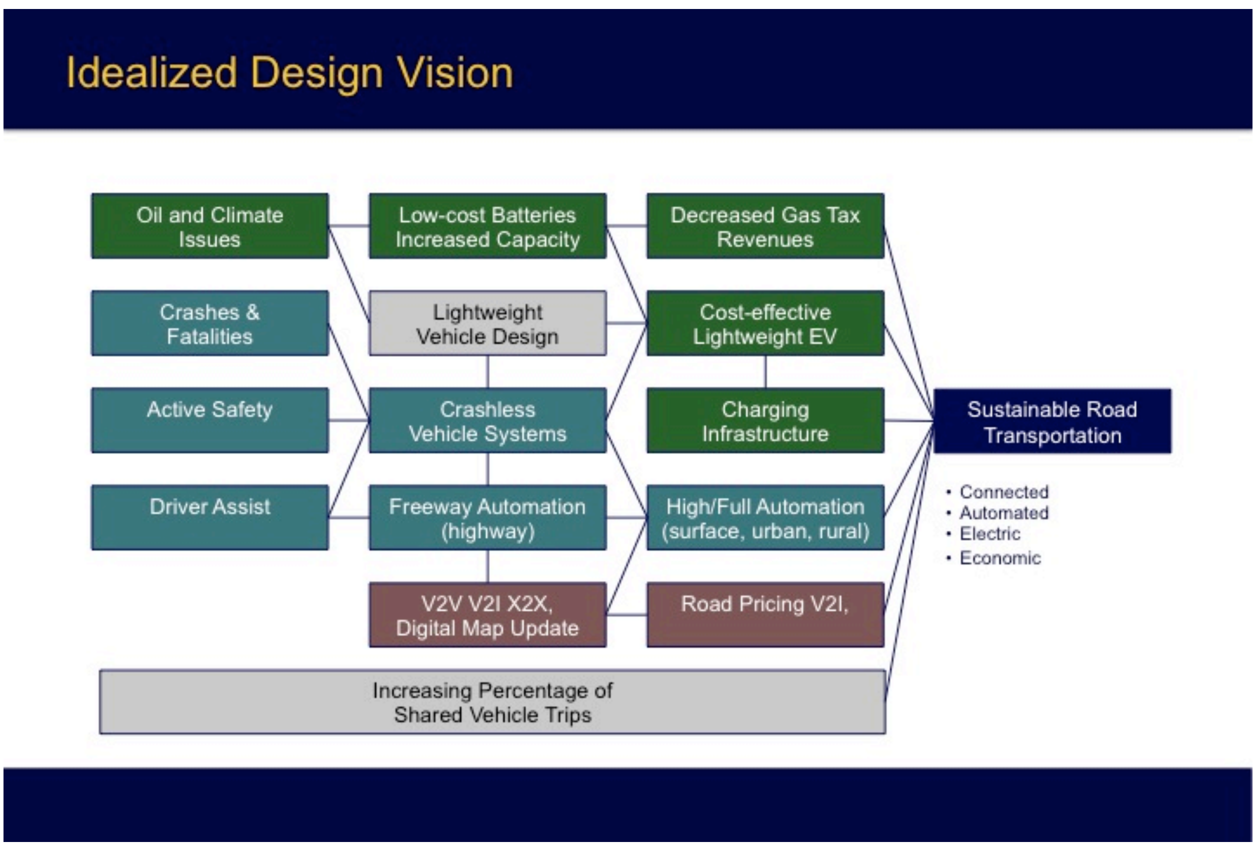
University of Michigan – Dearborn
TRB


SAE Convergence, Automated Vehicle System Market Introduction (SAE Levels), Median, IQR
5 FULL AUTOMATION
(Driver not required, e.g., robotic taxi)
Full Automation
2030
2035
Freight Platooning
2020
2025
Urban Highway & Surface
2020
Freeway
Shuttle
2018
(fail-safe)
4 HIGH AUTOMATION
Freeway
2020
(driver fallback)
3 CONDITIONAL AUTOMATION
2015
2020
2025
2030
S. Underwood
Institute for Advanced Vehicle Systems
University of Michigan – Dearborn
SAE


AUTOMATED VEHICLE SYSTEMS FORECAST, SAE
Low Speed
Shuttle Pedestrian Zones
2018
Valet Parking
Freeway Limited Access
Freeway Driving, take-over
2020
Freeway Driving, fail-safe
2020
Truck Platooning, drivers
2020
Truck Platooning, lead driver
Full Driver Replacement
Urban Driving
2025
"Taxi"
2030
Child to School
Before 2020
2020 2024
2025 2029
2030 2039
2040 & After
Never


Connected, automated, and electric…
…and eat more chicken!


Idealized Design Vision
Oil and Climate Issues
Crashes & Fatalities
Active Safety
Driver Assist
Low-cost Batteries Increased Capacity
Lightweight Vehicle Design
Crashless Vehicle Systems
Freeway Automation (highway)
V2V V2I X2X, Digital Map Update
Decreased Gas Tax Revenues
Cost-effective Lightweight EV
Charging Infrastructure
High/Full Automation (surface, urban, rural)
Road Pricing V2I,
Increasing Percentage of Shared Vehicle Trips
Sustainable Road Transportation
• Connected
• Automated
• Electric
• Economic

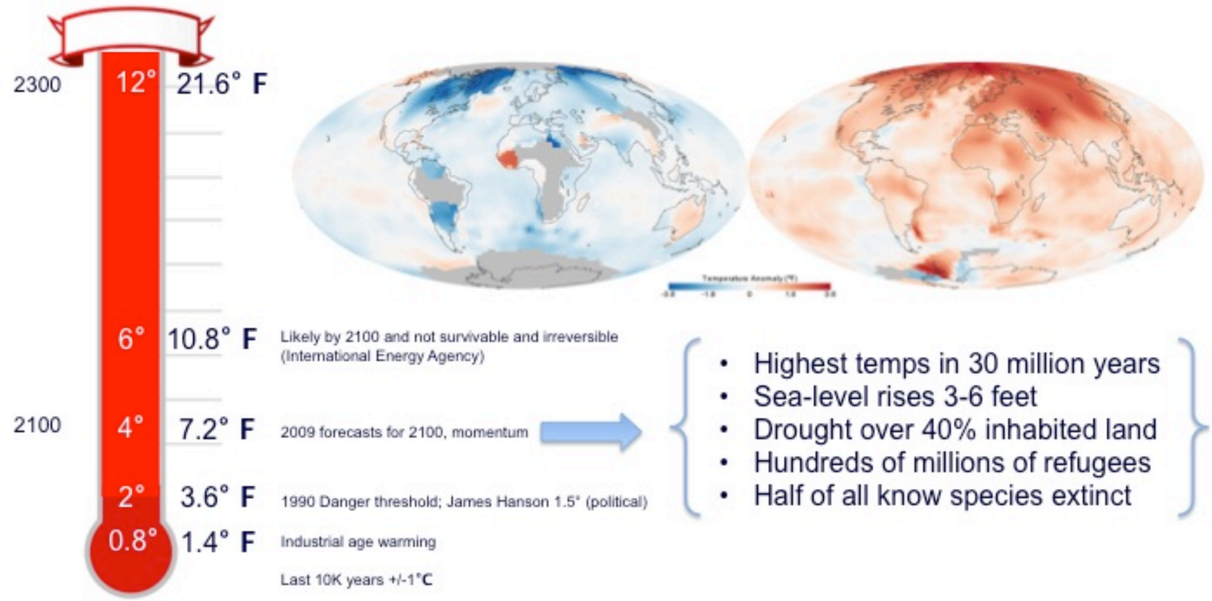
Advantages of Automated Driving

- **Relief from human driving: "**Chauffeur" feature reduces stress, monotony, fatigue, & full automation offers alternative for mobility disadvantaged, self driving shared vehicles/taxis
- **Free up "commute" time**: Safely and legally attend to communications, media, children, job-related, play, etc.
- **Precise maneuvers**: Parallel parking, vehicle charging, handling large vehicles, truck trailers, adjust speeds to reduce fuel and emissions, increase throughput
- **Reduced driver error**: Improved safety, "assertive" driving, no distractions, continuous "sensors on the road," ADAS backup, improved sensing, etc.
- **Compliance with regulations**: Increase safety with defensive driving, within traffic regulations,
- **Increased energy efficiently**: Platooning to reduce air resistance, efficient control of speeds, acceleration, deceleration, idling, etc.
- **Electric vehicles for Greenhouse gas reduction**: On-road and stationary inductive or direct charging of electric vehicles
- **Reliable**. Integrated or "fused" sensor system with fail safe, redundant, and safe harbor features.

Automotive Transportation Legacy in the US

- **Mobility in the US**
  - Automobile ownership, 828/1000
  - Interstate Highway System, 47,714 miles (2012)
  - Suburban development, parking, commutes
- **Personal and public expense**
  - Cost of vehicle ownership: depreciation, fuel, interest, insurance, maintenance and repair, tolls, parking, tax. Ford Fusion: $7K, BMW 750Li: $21.5K (Cons. Rept.)
  - Taxes and public expenditures: $20 billion per year more just to maintain infrastructure at the present levels
- **Fossil fuels and pollution**
  - Transportation uses 70 percent of oil consumed in the United States
  - 2.9 billion gallons of wasted fuel
  - Deterioration in air quality – 28% of US Greenhouse Gas Emissions due to transportation
- **Congestion and** delay
  - 4.2 billion hours of travel delay
  - $78 billion cost of urban congestion
- **Driver error and crashes**
  - 5.8M crashes/year (2009)
  - 2.5M injured, 33,963 deaths/year (2009)
  - Leading cause of death for ages 4 to 34
  - One collision every 18 years or 4 per lifetime, 1 injury per lifetime?
  - Direct economic cost of $230.6 billion (US 2000 data)
- **Time devoted to driving**
  - Average commuter spends 250 hours on the road/year
  - Urban Americans spend 5.5 billion hours sitting in traffic (2011, TTI)

IPCC: Fossil fuels must be gone by 2100 or we will pass a tipping point into a future calamity. (AP, 11/5/14)



Near Term Automotive Trends Related to Automation (next 5 years)

- Gen Y (born between mid 1970s to the mid 1990s, 24 per cent of the United States population in 2010)
- Small cars, micro cars, and EV growth markets
- Virtual Network Connections for tablets and smartphones
- Hydraulic to electronic (e.g., power steering)
- Penetration of by-wire actuation
- Lightweight materials
- Driver assist and active safety growing rapidly (ACC, ECS, BSD, LDW)
- High component cost coming down, function of volume, e.g., sensors including radar, and vision
- Sensor fusion and systems integration
- Sensor detection problems, not 100%, false detections, complex traffic environment, weather, light, etc.
- V2V and V2X is market ready
- Adopting ISO 26262, functional safety, Automotive Software Integrity Levels (ASIL A : 10-6/h - ASIL D : 10-9/h), long validation
- New validation methods using prototypes, interactive simulation and virtual reality
- Engine downsizing (e.g., reduction in displacement) and fuel switching (e.g., diesel), depends on gas prices
- Adoption of AutoSAR, MOST, and JAUS.
- Camera-based vision systems for traffic sign recognition, pedestrian detection, vehicle detection, lane following, night vision, and autonomous driving
- Usage-based insurance growth
- Voice and touch HMI along with larger screens
- Market shift to Asia and Eastern Europe