Disruptive Innovation on the Path to Sustainable Mobility: Creating a Roadmap for Road Transportation in the United States

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Abstract An ongoing study sponsored by the Graham Environmental 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 chapter describes the history of road transportation in the United States and the legacy of infrastructure investments in an automobile-oriented culture. This history is the foundation for applications of forthcoming robotics and communications technologies that support vehicle automation. A research team is engaged in drafting a roadmap that includes the adoption of automated vehicles as a critical element on a path to sustainable mobility in the United States. Some of the conjectures and apparent conclusions in this chapter are intended to help pose questions for our panel of experts.

Keywords Sustainable · Mobility · Automation · Autonomous · Connected · Telematics · American · Transportation

1 Introduction

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

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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.

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 chapter focuses on the future of telematics, connected vehicles, and automated vehicles the Graham study includes a forecast of electric and hybrid electric vehicles. Another chapter included in this volume 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 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 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.

2 History of Automotive Transportation in the United States

The United States is a quiltwork 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. 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.

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.

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 automakers 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.

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 [1]. 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.

3 Automotive Transportation Legacy

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. Accompanying this unrivaled expansion of investment automotive transportation was a parallel and related decrease in support for rail, private bus, and public transportation in general. Because of the reliance of automotive transportation the average American commuter spends approximately 250 h 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.

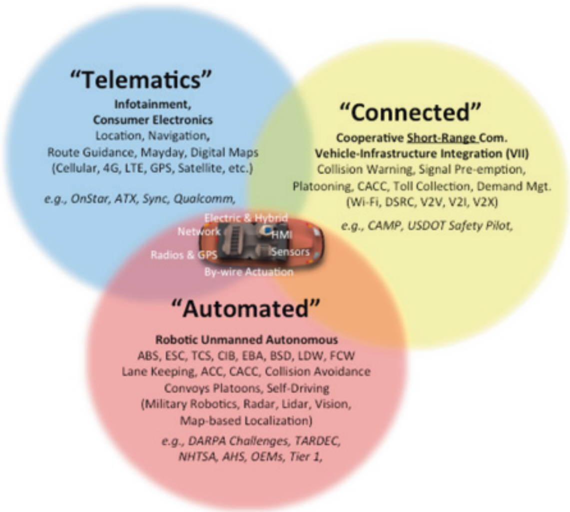
This is the leading cause of death for citizens between the ages of 4 and 34 years of age. According to the Texas Transportation Institute in 2011 Americans living in urban areas wasted about 5.5 billion hours sitting in traffic [2]. They also wasted 2.9 billion gallons of fuel with the total cost of 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 [3]. Many attribute the rise in obesity to the sedentary lifestyles associated with the automobile culture.

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. Nearly 30 % of all CO_2 emissions in the United States are caused by the transportation sectors.

Finally, if these 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. While the United States is still ranked number 12 out of 75 on the FedEx access index [4], indicating an ability to compete in world markets based on physical and information access including transportation, trade, and telecommunications, these important economic, environmental, and social consequences cited above bring into question the sustainability of automotive-centric transportation in the United States.

With regard to 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

Fig. 1 Three communities



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.

4 Three Communities

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." [5] 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 three communities in Fig. 1 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 will only be fully 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. Our plan is to conduct an IA that will 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.

4.1 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 of 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.

4.2 Connected Vehicles: Safety and Much More

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.

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.

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).

4.3 Automated Vehicles: 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 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 % of fatal crashes involve alcohol, distraction, and drug involvement or fatigue, it then 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 [6].

For the purposes of this chapter 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 as driver assist, conditional or limited automation, and fully automated or self-driving.

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.

Rather, the forecast will center 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

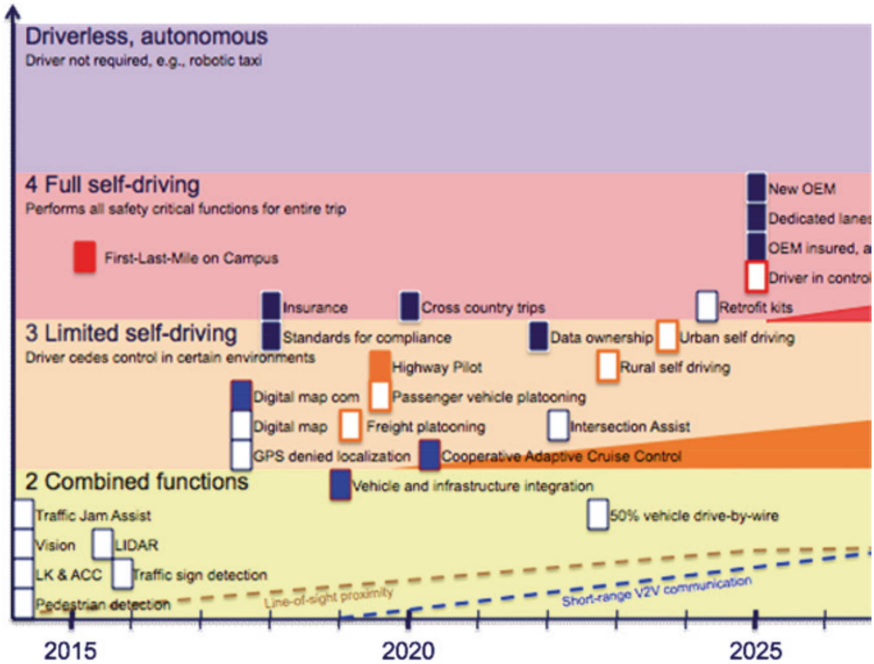


Fig. 2 Framework for delphi forecast

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).

The expert survey is designed to address the questions posed in this chapter. Figure 2 presents the conceptual framework for the technology forecast addressing three levels of automation (1) limited (2) conditions, and (3) full, over a period of years. The forecasts will address 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.

5 Conclusion

This chapter 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 last phase of the project will explore how these solutions will influence urban and regional planning for sustainable transportation.

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