Texas A&M Transportation Institute

Disruptive Technologies and Transportation

Final Report

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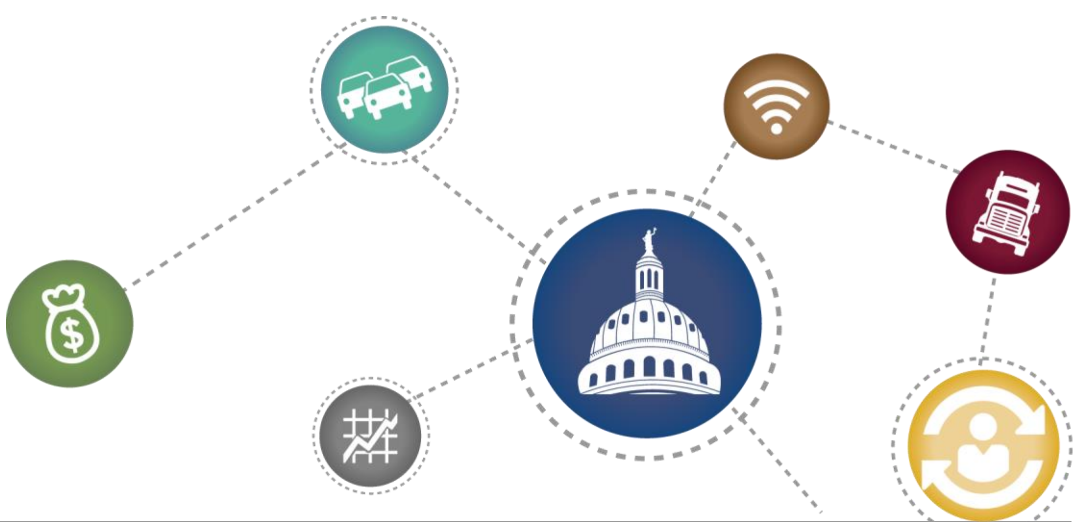

TRANSPORTATION
Policy Research CENTER

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Executive Summary

Disruptive technologies refer to innovations that, at first, may be considered unproven, lacking refinement, relatively unknown, or even impractical, but ultimately they supplant existing technologies and/or applications. In general, disruptive technologies and innovations:

- Are simpler, cheaper, more reliable, more popular, and more convenient than established technologies.
- Advance at a rapid pace and/or experience significant technological breakthroughs.
- Experience relatively fast penetration in the market.
- Have broad-based (as opposed to niche) markets and significant economic impact.

This report examines technology disruption with the objective of identifying areas where innovation may impact the transportation sector and associated policies. This report identifies five such areas:

- **Mobile Internet (MI)**—This represents the combination of mobile computing devices (such as smartphones and tablets), high-speed wireless networks, and associated applications. The penetration of smartphones in U.S. households is anticipated to continue, meaning many people will have access to the Internet and associated data and applications regardless of location. Demand on public agencies by drivers for more data-intensive services, such as real-time traffic conditions and advisories, could increase. However, the MI could also result in a decline in travel by personal vehicle and a decreased demand for roadway capacity. Various MI applications will reduce the need to own a vehicle as ridesharing services become more prevalent and mobile applications allow for the better planning of trips using alternate modes like transit. Furthermore, the ability to work remotely will reduce the need to commute to and from an office every day.
- **The Internet of Things (IoT)**—This refers to the use of sensors and data communications technologies embedded in physical objects, including roadway infrastructure and mobile devices, that enable those objects to be tracked, coordinated, or controlled across a data network or the Internet. Traffic management systems are currently capable of aggregating data from infrastructure-based devices to identify and measure traffic speed and volume on city roads, providing real-time data on traffic conditions and assisting in incident response activities. The IoT could change how transportation agencies manage their roadside assets, such as street lights and intersection signals, by allowing the real-time monitoring and control of these assets from remote locations. Furthermore, IoT-based technologies could provide significant amounts of data on the transportation system that might be used by MI-enabled travel applications or in automated vehicle operations.

- **Advanced materials**—This broad category includes nanomaterials, which are produced by manipulating matter at the nanoscale (less than 100 nanometers). This level of manipulation allows for the development of materials that may have greater reactivity, unusual electrical properties, and enormous strength. Nanomaterials such as graphene and carbon nanotubes could impact the transportation sector by providing strong, ultralight structural materials for use in various infrastructure development and construction activities. Advanced materials show the potential to significantly reduce the cost associated with maintaining transportation infrastructure. While they are generally high cost, their durability results in significant life-cycle cost savings and provides enhanced quality and safety.

- **Automated vehicle technologies**—These technologies allow vehicles to operate on roadways and navigate with little to no human intervention. There are currently numerous vehicle models that feature some degree of automation, but fully automated models are not yet available. These technologies could fundamentally change both how drivers interact with the roadway environment and how government agencies manage transportation infrastructure.

- **Immersive interfaces**—These technologies are generally characterized by interfaces such as a monitor (or other view screen) to view information and a keyboard or touchpad to enter information for use in interactive virtual reality environments. These technologies could result in new in-vehicle interfaces that display information without the need to divert attention from the roadway. On a wider scale, they could facilitate virtual reality applications that reduce the need for certain types of trips such as doctor's visits. Furthermore, immersive interfaces are likely to usher in a new generation of virtual reality simulation that could be used to model driver behavior.

After reviewing these technologies and technology applications, and identifying potential impacts to the transportation sector, the research team conducted a review of state statutes to identify areas of public policy that might warrant additional examination as these technologies develop. These policy areas include:

- **Demand for roadway infrastructure**—Many of the technologies and technology applications discussed in this report will likely change demand for roadway capacity, although it is not clear what that change in demand will look like. It is also not clear what the future model of personal mobility will look like because the traditional model is founded on the concept of personal vehicle ownership. Various technologies and applications reduce the need to own a personal vehicle by making it easier to access ride services, shared vehicles, or alternate modes like transit. The MI makes it easier for all travelers to access information on routes and travel times and to plan their trips accordingly. Many of these applications can be provided using third-party data sources and private service providers, potentially reducing the need for state and local/regional entities to provide these services. All of these issues raise questions about how infrastructure investment can be responsive to long-term disruption and how traditional revenue sources, such as fuel tax revenues, vehicle sales taxes revenues, and vehicle registration fees, might be affected.

- **Privacy and data security**—Privacy and data security concerns have emerged as a key issue with the growth of MI access and the emergence of the IoT. Furthermore, automated vehicle technologies may rely on vehicle-to-vehicle communications with other roadside assets or cloud-based systems, which would result in significant data privacy and security concerns. The current state code limits unauthorized use and possession of many types of data, restricts government and businesses in how they can share and use information, and establishes similar separate codes around digital medical information. From a security perspective, the risk of machines vulnerable to hacking becomes heightened as more and more devices and vehicles become connected to the IoT. Many of these issues are addressed through federal codes and rules of the Federal Communications Commission.
- **Standards**—Advanced construction materials could replace current materials used in routine pavement construction/rehabilitation and could lead to the replacement of current American Association of State Highway and Transportation Officials (AASHTO) and federal design and materials construction standards. Use of advanced materials could also lead to the replacement of current methods for life-cycle cost analyses and replace assumptions on quality and cost considerations that relate directly to transportation procurement and project selection processes.
- **State contracting and procurement**—The state's ability to use disruptive technologies in transportation service provision will likely be influenced by state procurement requirements because these technologies are, by definition, relatively unproven. Currently, material purchases may consider best value, which can allow for life-cycle costs to be considered in making purchases. However, overall life-cycle costs for many of the technologies discussed in this report are unknown, meaning that it may be difficult for governmental agencies to procure and use them.
- **Safety**—Many of the applications discussed in this report could potentially reduce safety while operating a vehicle, in particular MI applications that could be used in the vehicle and immersive interfaces that could result in less attention being focused on the roadway. **Regulatory**—Disruptive technologies may occur in regulated industries such as securities and taxi/transportation network companies. Rapid public adoption of these technologies may invite a reevaluation of existing regulatory structures.

Introduction

The concept of disruptive technology (and later disruptive innovation) is generally attributed to Clayton Christensen in his book *The Innovators Dilemma* (*1*). Christensen discusses developments in industries such as disk-based data storage and steel mini-mills as an examination of why some companies are unable to anticipate and/or leverage advancements in their respective industries and subsequently lose market share. Christensen argued that such companies rejected innovation based on the presumption that their existing customers had no use for new technologies or applications currently under development.

The companies examined by Christensen tended to focus too much on *sustaining* technologies, or those that are well known and undergo successive, often incremental improvements. Sustaining technologies change relatively slowly over time, with each new iteration representing an improvement in some aspect over previous models. This focus led to a dismissal of what Christensen termed *disruptive* technologies, which may be unproven, relatively unknown, lacking in refinement, or considered impractical. In many cases, these disruptive technologies tapped into new markets or displaced established firms in existing markets, leading to a realignment of major firms in the industries examined. For example, mainframe computer manufacturers in the 1970s and 1980s underestimated the potential demand for personal computers, allowing companies like Apple and Microsoft to disrupt the market with their new products. This innovation was disruptive because major manufacturers dismissed personal computers and overlooked a market that did not yet exist: households and small businesses that could not afford (and did not want) mainframes.

Today, the term *disruptive* is often used as a synonym for technological advancements that are simply different. Novelty, however, is not the same as disruption. In general, disruptive technologies and innovations are identified by the following characteristics (*2*):

- They are typically simpler, cheaper, more reliable, and more convenient than established technologies.
- They are advancing at a rapid pace and/or experiencing significant technological breakthroughs.
- They experience relatively fast penetration in the market.
- They have a broad-based impact (as opposed to appeal to niche markets) with significant economic impact.
- They eventually supplant existing technologies/applications.

This report examines the concept of disruption in a broad sense, with the goal of identifying potential disruptive innovations that may impact the transportation sector in the near term. For the purposes of this report, *disruptive technologies* refer to a broad range of technologies and technologically enabled applications. A disruptive innovation could take the form of a device, such as web-enabled smartphones, or applications, such as those found on a web-enabled smartphone. For example, social networking applications such as Twitter and Facebook are regularly cited as disruptive in that they changed the way society interacts. Even though they do not take the form of a specific, physical device, they are disruptive technology applications that rely on physical technology components like MI-enabled smartphones. Therefore, disruptive technologies and innovations are not, in this report, limited to physical devices.

Why Is Disruption Important to Policy Makers?

Current literature on trends in disruptive innovation tends toward several conclusions with implications for policy makers and transportation stakeholders:

1. Technological developments are occurring at an ever-increasing pace.
2. Technology adoption by the public has generally occurred at increasing rates.
3. Innovative disruption is difficult to predict.

Technological developments are occurring at an ever-increasing pace, a trend that is particularly true with regard to developments in computing-based industries. Moore's Law is commonly invoked in these types of discussions, which references Intel co-founder Gordon Moore's 1965 observation that "The number of transistors incorporated in a chip will approximately double every 24 months" (*3*). As a result, computer-based technologies and applications grow smaller, faster, and more powerful without significant cost increases. In many cases, increases in processing power lead to reductions in cost as a result of economies of scale. For example, the cost of sequencing the human genome has fallen by about $10 million in just over 6 years, largely due to enhanced (and lower-cost) computing capabilities as a result of Moore's Law (*4*). The implication of these trends for policy makers and transportation system stakeholders is that computing-based innovations will continue to grow in terms of speed and power, enabling a wide array of services that might currently seem infeasible.

Furthermore, the pace of technology adoption by the public has steadily increased over time. For example, it was not until 1945, well over 50 years after the introduction of the first consumer-based telephone and 30 years after the first coast-to-coast long-distance call in the United States, that even 60 percent of U.S. households owned a telephone. However, in stark contrast it took less than 15 years for 60 percent of households to obtain Internet service. The implication of these trends is that future disruptive innovations could see significant penetration within the consumer market in a very short period of time. It is possible that public-sector entities will not be able to react to and leverage these developments in a timely manner (*5*).

Disruption can be difficult to predict. Companies and analysts may attempt to predict disruptive innovation by performing supply-side analyses of other firms and their products to identify unique applications and business practices, or demand-side analyses of consumers and consumer habits to identify untapped markets. Regardless of the method employed, numerous variables can affect forecast accuracy, and in many cases disruption can only be identified and assessed after the disruption has already occurred. In fact, some high-profile venture capital efforts aimed at using predictive models of disruptive innovation to target capital investment have failed (*6*). The implication for policy makers is that it will be difficult to predict where disruption in the transportation sector will occur. Researchers and analysts can track trends, but the magnitude and impact of those trends can be difficult to assess. Disruption in the transportation sector has likely already occurred, and the public sector is likely to be asked more and more to react to changing paradigms rather than anticipating or guiding innovation.

Trends in disruptive technologies and applications have other implications for transportation policy makers. From a broad perspective, current disruptive technologies indicate that the nature of work is changing in the United States (*2*). Future companies will rely more on technology-based skill sets, which affects how governments approach public issues such as education. From a transportation perspective, disruptive technologies could change how the state of Texas anticipates and meets citizen expectations for mobility and invests in transportation infrastructure. Disruptive innovations can enable transportation entities to better monitor and manage assets while providing opportunities for the private sector to meet transportation needs without public-sector investment.

One of the best examples of a disruptive technology leading to broad changes in consumer behavior is the Internet, which has had a far-reaching impact on how consumers access information, interact with each other, and purchase goods and services. The disruptive influence of the Internet on consumer behavior and expectations has also led to changes in how government provides goods and services. For example, in recent years the U.S. Postal Service has seen significant shifts in demand for its services and the types of services it provides due to the proliferation of web-enabled email for communications and the use of the Internet for shopping. While consumers are less likely today to correspond through personal letters, there is an increasing demand for the movement of goods through the postal service as a result of online shopping. This means that the U.S. Postal Service has had to invest significantly in newer logistics technologies, such as advanced barcode scanning equipment, to compete with private-sector entities such as FedEx and UPS. There have also been shifts on the private-sector side of the postal industry. For example, Pitney Bowes, once a major provider of postage meters, is now focused on "customer information management, location intelligence, customer engagement, shipping and mailing, and global ecommerce" (*7*).

Disruption may not occur as the result of one particular technology development. Technologies and/or their associated applications may be repurposed to meet new needs and become disruptive. For example, social networking is not necessarily a technology but rather a technology application built upon another disruptive technology application: the Internet. The basic elements of social networking applications were already in existence long before social networking applications became popular: email, online forums, photo sharing, and personal blogging applications. However, by repackaging and marketing these applications, the developers of social networking applications disrupted Internet-based communications.

Literature on disruptive technology innovation is often focused on specific industries or product lines, making it difficult to compare trends and develop analytical frameworks that cross industries. For this effort, the research team identified a broad study conducted by the McKinsey Global Institute that identifies, classifies, and assesses the technological developments that could have "massive, economically disruptive impacts between now and 2035" (*2*). From that report, the research team identified five categories of technologies and technology applications that could significantly impact the transportation sector and change how Texas develops, maintains, and operates transportation infrastructure within the state. These categories include:

- **Mobile Internet**—This represents the combination of mobile computing devices (such as smartphones and tablets), high-speed wireless networks, and associated applications. Mobile devices are increasingly powerful and are capable of managing multiple applications at once using an array of embedded sensors and communications mediums. The penetration of wireless-capable smartphones in U.S. households is anticipated to continue, meaning that increasingly large numbers of people will have access to the Internet and associated data and applications regardless of location. One specific technological advancement that could impact the MI is the development of 5G data connections, which could provide 1-terabyte-per-second connections, similar in speed to current fiber-optic connections (*8*).

- **Internet of Things**—This refers to the use of sensors and data communications technologies embedded in physical objects, including roadway infrastructure and mobile devices, that enable those objects to be tracked, coordinated, or controlled across a data network or the Internet (*2*). Cisco estimates that 99.4 percent of the physical objects that may one day comprise the IoT have yet to be connected. Cisco further estimates that the potential value of these connections will be $4.6 trillion to the public sector and $14.4 trillion to the private sector (*9*). From the transportation sector's perspective, the IoT could significantly alter how government entities provide transportation services by allowing transportation infrastructure assets to be monitored and operated in real time from remote locations. For example, systems developed by IBM are capable of aggregating data from infrastructure-based sensors and similar devices in order to identify and measure traffic speed and volume on city roads. This provides agencies, and in some cases the motoring public, real-time data on traffic conditions, which can assist in incident response and routing activities (*10*).

- **Advanced materials**—This broad category includes nanomaterials, which are produced by manipulating matter at the nanoscale (less than 100 nanometers). This level of manipulation allows for the development of materials that may have greater reactivity, unusual electrical properties, and enormous strength (*2*). Nanomaterials such as graphene and carbon nanotubes could impact the transportation sector by providing strong, ultralight structural materials for use in various infrastructure development and construction activities, potentially reducing the cost of materials and the length of time of construction.

- **Automated vehicle technology**—This category encompasses a wide range of in-vehicle sensing, communications, and computational technologies that allow for an increasing array of complex driving tasks to be performed on an automated basis with little to no human intervention. Numerous vehicle models currently on the roadway feature some form of automated operation such as adaptive cruise control or automated parking. However, there are no fully automated models available on the market. Automated vehicles could fundamentally change how drivers interact with the roadway environment and how government agencies operate and manage transportation infrastructure.
- **Immersive interfaces**—These technologies represent a transition from the traditional model of technology interaction, generally characterized by interfaces such as a monitor or other view screen to view information and a keyboard or touchpad to enter information toward virtual reality interactive environments.

About This Report

In this report, the research team discusses these technology groups in more detail, with a focus on identifying how Texas might leverage these systems. Examples of specific technologies or applications are discussed for each category, and potential impacts to the transportation system are explored. Furthermore, this report discusses how these technologies are potentially disruptive and the potential impact of this disruption. The report closes with a discussion of policy implications from the continued evolution of these technologies and technology applications.

Mobile Internet

The MI refers to the ability of mobile devices, such as tablets and smartphones, to connect to the Internet. It is increasingly common for vehicles themselves to feature devices capable of accessing the Internet as a standard feature. The MI is supported in large part by the nation's high-speed cellular 4G network and the growing coverage of wireless-radio-based telecommunications mediums (such as Wi-Fi) in urban areas.

The MI has the potential to provide the highest amount of economic benefit of disruptive technologies discussed in this report (*2*). This is due in large part to the general integration of the Internet into virtually every aspect of the economy and the everyday lives of drivers. The MI increases the ability of citizens to access the Internet no matter where they are, which can significantly change the way people travel and make use of transportation services. The MI has implications for the public sector in terms of how to meet new transportation service demands. For example, the MI is increasing the viability of remote work locations, and it is unclear how commuting trends and associated demands on roadway capacity may be impacted in the long term. Additionally, the MI will have significant implications for personal mobility because ridesharing services are becoming an increasingly viable alternative to personal vehicle ownership.

The MI is not so much a disruptive technology itself as it is an ecosystem for the development of disruptive applications (apps). As the MI grows and matures, the potential for disruption increases as newer and better apps and services are developed.

Transportation Applications and Impact

The Internet itself can provide any number of valuable travel-related services to drivers. Drivers could get information on traffic conditions, find alternate routes to save time, and plan trips using alternate modes such as transit. Before the advent of the MI, these services could only be used from a location that had Internet access, such as a home or office. However, the MI makes the Internet and associated travel services available from almost any location with an Internet-capable device.

What makes the MI particularly interesting from a transportation perspective is the growing prevalence of vehicles capable of accessing the Internet. Right now, the MI is composed mostly of smartphones, tablets, and portable devices that allow for access to the Internet from almost anywhere. However, it is increasingly common for newer-model vehicles to feature cellular-based Internet connections and onboard Wi-Fi. This allows for the expansion of vehicular based-services that can be provided through an in-vehicle interface. In addition to simply accessing the Internet for things like entertainment, vehicle drivers and passengers will be able to access web-enabled applications such as routing assistance and concierge services.

The proliferation of the MI is already having an impact on how governments provide services. With enhanced connectivity, citizens expect to have more services and government functions available through the Internet, spurring the advancement of e-government initiatives that seek to make public data more widely available for application development, and enhancing the government's ability to provide services via the Internet. The City of Chicago is an example of a local government at the forefront of e-government and open-source government, with the city's mayor recently appointing the city's first chief data officer to lead city-wide open data reorganization (*11*). The city has developed the Open311 mobile phone app, a new public interface with the city's 311 system that allows citizens and departments to access a simplified system for submitting and tracking work requests that can be tracked by individual departments (*12*). The integration of e-government into public services is seen as potentially reducing wait times for services due to more accurate scheduling, providing for quicker response times without the need for a human interface, and providing citizens with more opportunities to provide feedback on service quality.

The MI also provides citizens with opportunities to monitor government services in real time. For example, in an effort to provide its residents with real-time data on snow removal activities, the City of Wichita, Kansas, recently equipped all of its snow plow equipment with global positioning system (GPS)–based transponders. Through a computer-based or mobile-based connection to the Internet, area residents are able to look at a map that shows where the city's snow plows are active and where they will be running.

The data that can be accessed through the MI for real-time monitoring of public services have significant implications for local transit service providers. It is increasingly common for transit providers to equip buses with communications and location equipment that allows their location and speed to be monitored in real time. Transit riders can monitor the location of vehicles and time their departure for the transit stop accordingly, which reduces time unnecessarily spent waiting on a vehicle at a transit stop and allows users to more efficiently plan routes by allowing for better calculation of arrival times.

Furthermore, the MI allows transit agencies in rural areas to more efficiently plan and manage their routes through the use of flex routing, which combines traditional fixed-route transit service with on-demand transit service. Flex routing has traditionally been used in paratransit applications, but an increasing number of transit agencies are using this strategy as a way of providing transit services in areas with low ridership. For example, the City of Houston will be using flex routes to improve services in suburban neighborhoods by allowing users to call in a request for point-to-point service within designated flex zones. Riders can also get dropped off at a neighborhood transit center (*13*). Flex-routing services have been available for many years, but growth in smartphone ownership and other mobile devices has increased the demand for services that can be provided through those devices. Flex-routing services can use data from riders' smartphones to adjust routes to maximize ridership and/or improve travel times while reducing costs compared to traditional fixed-route service. These types of services could be potentially valuable in rural, small urban, and other low-service transit areas that might not have the ridership to support traditional fixed routes. Flex routing may also be applied in other public-sector activities, such as postal services, because it allows for short-term re-routing to maintain peak efficacy by adjusting routing and/or the time of day of travel in order to avoid short-term obstacles or traffic.

Many cities are using sensing and communications technologies (discussed in more detail in the IoT section of this report) to provide enhanced parking services. Next-generation parking garages and lots are increasingly capable of identifying available parking spaces and relaying that information to potential users through a mobile device. ParkPGH in Pittsburgh, Pennsylvania, and SFpark in San Francisco, California, are two parking apps that allow users to view available parking in city centers. ParkPGH uses historical parking garage usage rates and an algorithm developed by Carnegie Mellon to provide projected open spaces per garage (*14*). SFpark is a city-sponsored effort that placed sensors in certain downtown blocks to detect if a car is parked in a city parking space. This technology also includes a future ability to adjust the cost of public street parking, creating a dynamic self-balancing parking system (*15*).

Many of the MI-enabled services discussed so far, such as e-government, transit flex routing, and parking, are supported by e-payment systems, which have also expanded as a result of growth in the MI. Mobile-device owners can obtain and pay for a ridesharing service/transit, or pay for other government services through their phone without the need to process a credit card or debit card payment on the spot or carry cash. Online payment systems and the integration of other electronic payment-enabling systems, such as radio frequency identification (RFID) chips and near-field communications systems, can increase the ease with which payment can be obtained from system users, decreasing overhead collection costs. This is particularly true for transit operations, where RFID-enabled mobile phones can be used to quickly pay for transit fares by swiping the phone across a specialized receiver in the bus. This can help to decrease boarding times and increase the efficiency of transit operations.

There has been a push in the United States to use touchless RFID cards to integrate multiple modes of public transit. Seattle's ORCA Card uses a single payment platform to access ferry, train, and bus transit modes (*16*). In Europe, this integrated system has allowed for innovative partnerships between tourist economies and transit. Seoul, South Korea's T-Money card currently works as an RFID card or mobile payment app, allowing tourists to use the T-Money system to access transit and make payments at multiple tourist destinations. In recent years, Chicago's touchless Ventra pass has begun to explore a similar integrated model (*17*).

The MI has the potential to significantly impact the traditional model of personal mobility, which has typically involved personal vehicle ownership, with alternate modes (such as transit, walking, and bicycling) for those who do not own a vehicle or choose not to drive one. The MI has the potential to shift this model away from mobility based on personal vehicle ownership and toward a model of mobility as a service that can be used when needed without owning a vehicle. There are an increasing number of applications and services that connect travelers to vehicles for short periods of time or specific trips, reducing the need to own a personal vehicle.

Recent examples of applications that package mobility as a service include transportation network companies such as Uber and Lyft, which for the consumer take the form of a web-based mobile-phone app. These systems generally work by connecting people in need of a vehicle with available drivers and vehicles. Users select their location (and in some cases destination), and the app finds an available driver and directs that driver to the users. The user is notified of the impending arrival of his or her vehicle and driver, with locations being determined through GPS data generated by the driver and user's phones. Payment for the ride occurs through the app itself through a credit or debit card. Uber provides additional customization, with users being able to select from different types of services such as UberXL (which has vehicles accommodating more people), UberBLACK (which features luxury drivers and licensed chauffeurs), and the low-cost uberX. Drivers receive real-time routing information for directions, and a social rating system is used to provide user feedback. All of these services and their associated components are supported by the MI, and services can be expected to improve with higher levels of computing power in mobile devices and better integration between services. Improvements are also likely to occur with the continued development of the fifth generation of mobile technology (5G), which is anticipated to enable "a fully mobile and connected society" and will "empower socio-economic transformations in countless ways, many of which are unimagined today" (*18*).

These types of apps have already caused some disruption within the taxi industry, where they essentially fill the same role as a taxi. While there is an approval process for drivers, it is becoming increasingly common for private vehicle owners to act as Uber or Lyft drivers in their spare time or full time. Taxi cab organizations and others have objected to Uber operations in many U.S. cities due to the lack of regulation of these services.

Other types of services provide a narrower service but nonetheless rely on the MI to present service options to those needing to travel. Services like Zipcar, Car2Go, or Flightcar are mobile-based services that direct people to nearby vehicles that are available to rent. Users enter their location, and the mobile app directs them to the nearest available participating car. Payment for use of the vehicle is accomplished through the app.

The MI is likely to also significantly change the way that transportation-related data are generated and used by drivers, the private sector, and the public sector. Mobile devices and MI-capable vehicles are capable of not only accessing data but also generating data. Mobile devices and the apps they run are often capable of collecting information while travel is occurring, which can be fed back into the data systems supporting the app and help refine the services being provided. These crowd-sourced data can be tapped to provide any number of services for private users and private entities, but they may also be tapped by local, regional, and state transportation agencies for use in operating and maintaining transportation infrastructure and providing transportation-related services.

For example, WAZE collects GPS data and information directly input by users regarding traffic conditions, such as incidents or congestion on specific roads, which allows the system to find routes for other users that bypass congestion and save time. This data collection is accomplished by users activating the app once they have found their routes and are beginning to drive, generating travel data for the system to use. These users are able to provide road reports, such as the occurrence of vehicular incidents or the presence of a speed trap, through the app that are then used by the larger WAZE community to make their own routing decisions.

Current Applications by Transportation Agencies

The Florida Department of Transportation (FDOT) currently has a data-sharing agreement with WAZE wherein WAZE data are used to supplement data generated by the state's network of intelligent transportation system (ITS) infrastructure. Florida drivers can access FDOT web resources and find traffic information on state roadways with the WAZE data providing extra clarity. For example, FDOT data may show that traffic volumes and travel times on a certain roadway are increasing significantly, while the WAZE crowdsourced data provide an eyes-on-the-ground perspective that shows whether these slowdowns are from debris in the road, a vehicular incident, or other causes. As noted earlier, WAZE allows its users to know the location of law enforcement activities such as speed traps, and there were concerns in Florida about allowing this type of data to be shown on department of transportation–maintained data services. However, FDOT has indicated that it would prefer people to know the location of speed traps because its primary concern is that drivers operate their vehicles safely. If being aware of speed traps makes drivers more cautious and less likely to speed, then FDOT does not object to making the information available on its websites (*19*).

Crowdsourcing may also be used to generate data specifically for use by transportation officials. For example, accelerometers and gyroscopes are among the many sensors that are often found standard in newer-model smartphones. The City of Boston sponsored the development of the Street Bump app, which, when activated by users, collected information on the smoothness of the ride. The sensors on the phone detect potholes and poor road conditions that affect the quality of the ride, and this information is fed into a database that the city can analyze to prioritize road maintenance. The app is free to potential users (*20*). Furthermore, cities and their private partners are developing mobile apps that allow citizens to quickly identify local infrastructure issues by reporting traffic timing issues or taking geo-referenced pictures of things such as damaged sidewalks.

In Austin, users can use a ridesharing app called Carma, which connects riders with drivers but does not involve the exchange of money. The app works by pairing people with similar commutes and schedules so that they can share a vehicle. The program is sponsored by the Central Texas Regional Mobility Authority with the objective of reducing the number of people driving in their vehicle as the lone occupant, potentially reducing the number of vehicles on the road. In areas that have high-occupancy vehicle lanes or high-occupancy toll lanes that provide expedited trips through traffic for vehicles with two or more people, programs like Carma provide an opportunity to increase vehicle occupancy and use these facilities for a quicker, less congested commute.

Other services simply provide information to users on the best options available for them to reach their destination. Users of apps such as Metropia, RideScout, and WAZE enter their location and destination, and the apps use data from various sources to calculate the travel time and cost of the trip based on mode. For example, a user of these apps would know how long it would take, and at what cost, to make the specified trip using a ride-sharing service, the local transit system, a bicycle from a bike-sharing service, or simply walking.

Internet of Things

The IoT represents an expansion of the Internet to include physical objects. Devices and objects, once connected to the IoT, will generate data for users who will have the ability to control those devices and objects through a simple Internet connection. This will be accomplished through embedding sensors and sensor-connected motors (or actuators) in machines and other physical objects to bring them online and allow for remote access and, in some cases, control. McKinsey & Associates estimates that there are currently 9 billion devices around the world connected to the Internet and estimates that by 2025 that number will grow to between 50 billion and 1 trillion (*2*).

The IoT already has numerous applications in the everyday lives of Texas residents. For example:

- Home owners will be able to remotely monitor and control household systems such as heating, air conditioning, or home security systems.
- Health care providers will be able to remotely monitor patients with chronic diseases through wearable technology or sensors embedded within devices like heart monitors.
- Utility providers will be able to better monitor electricity grids and water systems to improve conservation.

Much like the MI, the IoT is not so much a disruptive technology innovation itself as it is an enabler of future disruption. The MI will increase the ability of citizens to access the Internet no matter where they are, while the IoT will significantly increase the number of things that can be accessed through the Internet. Through the IoT, private businesses and public-sector transportation organizations can develop connected, data-driven business and program processes aimed at improving how they manage assets, optimize performance, and improve customer satisfaction. For example, Daimler Trucks North America offers freight companies a service where sensors are installed to monitor vehicles and communicate data on route travel times, vehicle malfunctions, and travel speeds to a central communication center (*21*). Malfunctioning vehicles can be routed to service centers that have the parts and capabilities required to fix the issue, minimizing potential down time.

Transportation Applications and Impact

In a transportation setting, IoT-related applications are already being used in any number of applications, such as:

- Businesses monitoring the flow of goods through the complete supply chain via RFID tags embedded in commodities, production equipment, and vehicles.
- Drivers remotely monitoring vehicle health and accessing vehicle diagnostic data related to fuel consumption, emissions, and electrical system health and status.

- Transportation agencies and private partners using data collected from sensors on smartphones to generate traffic data that can be relayed to dynamic message signs.
- Transportation agencies using remote sensors to monitor the health of traffic control devices, such as stop lights, and monitoring other aspects of the transportation system such as road conditions.

The IoT is enabled by information technology and specifically information and communications technologies such as 4G wireless signal networks that:

- Trend toward rapid technology advances.
- Follow exponential trajectories of improvement in cost/performance.
- Are characterized by a network effect that increases value to users as more users sign on to the service.

The IoT has the potential to rapidly change existing business practices and service delivery models for the public and private sector. One example of the potential for disruption is found in the most basic components of the IoT and its earliest application: RFID. Current RFID technologies are already enabling IoT development through the use of inexpensive stickers and tags placed on freight supplies and a multitude of other items such as fleet vehicles that enable the automatic identification and tracking of the tagged items based on the information contained within each tag. In 2003, Walmart announced a mandate requiring top suppliers to put RFID tags on shipping crates and pallets for the purposes of logistics and inventory management. As a result, RFID startup companies proliferated. What has come out of the RFID mandate is a realization of the value of instantaneous transfer of freight data and the impacts of this transfer on supply chain logistics and management.

The expedited tracking and verification capabilities of RFID technologies have already been deployed in numerous public-sector service settings. Simple RFID sticker tags are already widely used throughout the United States as a means of electronic toll payment. Furthermore, U.S. Customs and Border Protection is using RFID technologies to allow for expedited border crossings as part of its Ready Lane program. The Ready Lane program features dedicated lanes at land border ports of entry where travelers who obtain and travel with a special RFID-enabled travel document may receive expedited inspection of their vehicle and subsequent entry into the country. Texas-based Ready Lanes are available at the following international border crossings: Del Rio, El Paso (Ysleta-Zaragoza Bridge, Bridge of the Americas, and Paso Del Norte), Progreso (Donna-Rio Bravo International Bridge), Eagle Pass (Bridge 1), Brownsville (Gateway Bridge), Hidalgo, Laredo (Lincoln-Juarez Bridge), and Pharr.

Potential Applications by Transportation Agencies

The proliferation of more advanced sensor and communications technologies as part of IoT development could have significant implications for how state and local agencies manage and operate equipment such as traffic signals and other traffic control devices. Equipping such devices with IoT-capable functions can allow for remote monitoring of this equipment, which could reduce the need to do maintenance and monitoring of equipment in the field. In this example, traffic signal health could be monitored remotely through an Internet connection using the specific IP address for the signal, removing the need to send a technician into the field and reducing the costs associated with maintenance of this infrastructure. Additionally, government fleets can be outfitted with devices that allow for remote tracking and monitoring. The application of the IoT components to governmental assets in general will facilitate the development of enhanced performance management systems by allowing for the convenient tracking of asset performance (*21*).

Furthermore, the growth of the IoT could change how state and local transportation agencies manage traffic and congestion on their respective roadway networks. The use of IoT components in infrastructure could spur the development of traveler information hubs that could replace traditional traveler information systems. The general proliferation of IoT-enabled devices would provide a wealth of data that might be used to refine and optimize planning, programming, and operations of infrastructure by transportation agencies. Equipped devices could relay information back to the transportation hub that could enable certain traveler services such as real-time routing assistance and congestion notifications. These systems would likely reduce data, maintenance, and ITS program monitoring costs (*22*).

In the United Kingdom, the STRIDE pilot program created a single IoT information hub for transportation users along a designated corridor that served an interconnected network of smart devices including sensors in roads, vehicles, transit, rail, airports, and smartphones. The hub supported real-time information sharing among businesses, things, and people, allowing multiple data sources to be stored within a single uniform interface. As part of the pilot, government policy established the information hub as a trusted broker, which means that individuals and businesses have the choice to use the hub to share data with only organizations of their choosing. Underpinning this hub was the British government serving as the sponsor, enabling users to safely contribute their data in support of an ecosystem of multiple vendors and their business endeavors, as well as government operations including transportation systems, management, and operations. Services providing driving behavior assessments to drivers are protected from having to turn this information over to the government if the driver does not wish to share this information. Passengers wanting to contribute this and other smartphone-sensor-based information such as weather and travel speeds to the transportation agency are able to do so (*22*).

IoT-capable sensors and communications technologies will also allow the expansion of government services that might be provided through the MI, which was discussed in the previous section of this report. Sensors in buses and smartphones will enable the refinement of flex routing as part of local and regional transit operations by providing data that can be used to develop dynamic headway information for the transmission of real-time bus location data to transit users. This information could be used to supplement and/or replace existing transit scheduling practices and reduce system operations costs (*23*). Local agencies could benefit from IoT-enabled parking garages that replace traditional parking garages. Equipment could monitor available parking spaces and notify a centralized system when the facility is at capacity. Drivers could access this information through the Internet or a mobile smartphone application.

Advanced Materials

The world science community is continually developing new advanced materials that could have immense applications for consumers but will also have highly desirable attributes for the transportation industry. Some of the most recent developments in advanced materials include:

- Smart nanotechnology and biomimetic materials with self-healing or self-cleaning attributes.
- Metals featuring shape memory that can revert to their original designed shape if deformed.
- Piezoelectric asphalt mixes that turn pressure into energy.
- Miniaturized fiber-optic sensors embedded in asphalt mixes that make the road capable of providing self-diagnostics (*2*).

Nanomaterials describe materials in which single units of that material area measure at between 1 and 1,000 nanometers (10^{-9} meters); however, the term is often applied to slightly larger materials. Buckminsterfullerene (or Bucky Balls) is a well-known nanomaterial and has that designation because its special properties are due to the unique shape of its molecule: 60 carbon atoms arranged in a soccer-ball-like structure featuring 20 hexagons and 12 pentagons. Due to the miniscule nature of the materials, they are difficult to develop. However, in recent years nanomaterials in general have seen an extremely high rate of improvement and reduction in cost. As costs come down, their application to consumer goods and industries such as transportation become more feasible. Nanomaterials retain great electrical conduction properties and enormous strength per unit of weight. They enable a variety of transportation improvements such as super-slick coatings for highway signage, bridge paints with reduced corrosion patterns, and stronger roadway asphalt mix composites. They can also enable the development of ITS roadway sensor batteries with higher charge capabilities and longer life cycles. Nanomaterials such as graphene and carbon nanotubes also contribute to efforts to create super-efficient batteries such as lithium-sulfur batteries and improved solar cells (*24*).

It is difficult to estimate the extent to which advanced materials might impact consumer goods. They might be incorporated into various goods to increase durability, reduce weight, or provide other improvements to physical attributes. Furthermore, advanced materials could enable the development of improved batteries and sensors for use in mobile devices and other technologies.

Potential impact to the transportation sector is similarly wide ranging. Nano-carbon composites, bio-concrete, and fiber-optic sensors that can be included in innovative new surface layer pavement mixtures and bridge construction will increase initial construction costs while decreasing life-cycle maintenance costs and extending overall infrastructure life. Existing roadway pavements consist of asphalt pavements and concrete pavements. When a road is categorized as concrete or asphalt, it really is an indication of the material used for the surface layer, which typically uses higher-quality materials because that layer will be most exposed to the elements and wear and tear of use (*25*). The Federal Highway Administration (FHWA) has funded research aimed at improving the quality of these surface layer materials at the nanoscale. In 2008, FHWA funded a study examining the use of stress-relaxing cementitious composites, including carbon nanotubes, which would be embedded within concrete at the nanometer to micrometer scale to reduce the brittleness of roadway concrete and reduce cracking. These materials could reduce the incidence of cracking due to concrete shrinkage, thermal changes, expansive corrosion reactions, and alkali-silica reaction expansions. If successful, this research could lead to the development of new concrete additives that could significantly increase the service life of new concrete infrastructure, lowering the maintenance costs associated with roadways (*26*).

Piezoelectric pavements, which convert the mechanical energy of a vehicle passing over the roadway into electrical energy, were first explored in Israel starting in 2009. However, it was found that roads using piezoelectric materials reduced vehicle fuel efficiency (*27*). Since that time, the technology has advanced considerably and is being evaluated for potential use in the United States. FHWA notes that piezoelectric technologies within a roadway environment have two advantages: energy that would normally be lost through pavement deformation and vibrations from vehicles can be captured, and piezoelectric materials may help facilitate the deployment of a smart-sensing network capable of providing information on the integrity of pavement structures. To that end, FHWA is funding research exploring a kinetic-to-electric conversion (KEEC) system that could be deployed to harvest the mechanical energy of vehicles passing over pavement. The system works by exploiting the electric charge that accumulates in some materials when a force is applied. The KEEC system consists of multiple generators that are constructed of thin piezoelectric ceramic and polymer layers. Researchers will develop and test a KEEC system under real and controlled roadway conditions. FHWA notes that the successful deployment of such systems would not replace major power sources but could offset the costs associated with roadway operations by providing electricity for operational functions such as street lighting and intersection signals (*28*).

Advanced materials could also have implications for roadway maintenance implications outside of simply pavement. FHWA estimates that corrosion of steel bridges from exposure to moisture and atmospheric pollutants like chlorides and sulfates costs the nation an estimated $500 million on an annual basis. Therefore, FHWA is currently studying the use of nanomaterial-enhanced corrosion-resistant coatings that might be easily and quickly applied to steel structures in order to provide better overall protection to roadway infrastructure and specifically protection against corrosion. In the first phase of the project, researchers at City College of New York examined two experimental additives for structure coatings:

- A polyaniline epoxy system with high electrical conductivity.
- A nanomaterial-enhanced calcium sulfonate alkyd system or Nanoclay, which is less costly than other nanomaterials.

Researchers are currently testing new additives that might be incorporated to improve performance of the coatings. The results of this research should allow for the calculation of life-cycle cost savings from employing new non-materials for structural protection. FHWA hopes that these types of materials will lead to the wider development of nanomaterials for use in transportation infrastructure maintenance, which will lower life-cycle costs while improving performance (*29*).

Automated Vehicle Technologies

Automated vehicles are a combination of technologies that enable a vehicle to assist in the task of driving. They can operate at varying levels of automation, from no automation (where the driver is in complete control of the vehicle) to full automation (where in-vehicle systems assume full control of throttle, braking, and steering controls). Many vehicles currently on the road feature some form of vehicle automation, be it adaptive cruise control or parking assist functions, but no fully automated vehicles are on the roadway at this time. Those vehicles that do possess high levels of automation can generally only operate in automated mode under certain conditions, and in most cases, the driver must resume control of the vehicle if a problem is encountered during automated operation. However, the field of automated vehicles is rapidly advancing, and fully automated vehicles could be on the road anywhere from within the next few years to a decade from now. This section of the report discusses the development of these high-level automated vehicles and their potential impact on Texas' transportation system.

Automated vehicles rely on a variety of technologies to function. First, the vehicles use previously developed high-definition maps of the roadway environment, which provide a reference point for navigation. Automated vehicles then use high-accuracy location technology (such as that obtained from GPS) to determine where the vehicle is, and onboard sensors and vision-based systems (such as LiDAR, radar, and ultrasonic devices) to detect and compile information about the dynamic road environment.

The timeline for anticipated automated vehicle deployment is unknown. Currently, basic vehicle automated features, such as adaptive cruise control and imminent collision braking, are found in newer-model cars. However, there is no consensus on when vehicles that assume full control of the vehicle for roadway driving will be widely available to the public. However, many manufacturers, such as Telsa, have indicated that they will have fully automated vehicles within the near term. Furthermore, automakers and in-vehicle system developers are continually testing and refining automated vehicles and their associated components. An Audi SQ5 outfitted with Delphi components recently completed what is being billed as the first coast-to-coast trip in an automated vehicle. The vehicle traveled through 15 states in nine days, logging about 3,400 miles, 99 percent of which were accrued under automated conditions. Google continues to expand its own automated vehicle tests, recently announcing that one of its automated vehicles would be tested in Austin, Texas.

Transportation Applications and Impact

Vehicles with a high level of automation could represent a significant portion of the vehicle fleet in the long term due to their potential for increased safety, efficiency, and convenience. If automated vehicles are as effective as predicted, they have the potential to disrupt many governmental functions. For example, the nature of many government jobs that require a human driver, such as transit operations, mail delivery, sanitation services, and law enforcement, could change. Each of these areas could be disrupted by a vehicle that can consistently and safely drive itself, but it does not mean that humans would no longer be needed in that area. In the case of mail delivery, for example, a human might still be needed to actually deliver a parcel. Until advances in automated vehicle systems become more established and available on the market, it will be difficult to accurately assess the potential impacts to both public- and private-sector jobs.

In the general sense, automated vehicles will reduce the need for humans to be actively engaged in driving. In terms of broad, societal impacts, it is possible this will decrease crashes and result in improved safety because the majority of crashes and fatal crashes are attributable to human error. This could be a significant benefit to Texas drivers because the annual costs of fatal crashes alone are significant. Enhanced safety from automated vehicle systems could impact the insurance industry, which is still in the process of assessing how these systems would impact their ability to identify driver risk and assess premiums based on that risk.

On a more individual scale, automated vehicle systems have the potential to significantly disrupt how people travel. It is unknown how automated vehicle systems will ultimately interact with the roadway and non-automated vehicles, but the mere potential for drivers to disengage from the driving process and engage in other activities opens up a wide array of potential in-vehicle services. Entertainment-based services could potentially be in greater demand. The demand for these services could drive demand for increased connectivity within the vehicle. Many new-model vehicles are already capable of acting as Wi-Fi hotspots, and it is likely that this connectivity will increase regardless of the pace of advancements in vehicle automation.

As noted in the MI section, there is increasing recognition of a shift away from a vehicle-ownership-based model of transportation and toward a transportation-as-a-service model. Automated vehicles could accelerate this shift, assuming that they are able to operate on a public roadway without a human even being present. For example, it is possible that a person who does not own a personal vehicle but has an immediate yet temporary need for one could summon an automated vehicle through an online portal or mobile-phone-based application. Once the trip is complete, the vehicle could be routed automatically to the next person in need, foregoing the requirement that the driver return it to a certain location for access by subsequent users.

Many governmental services could be impacted by automated vehicle development, in particular those that use vehicles for the services being provided. Public transit, sanitation services, and mail delivery could all be disrupted by a reduced reliance on human drivers. Increased efficiency and effectiveness of vehicle travel could be a substantial benefit to governmental agencies, such as transit providers, who spend significant sums on salaries and benefits for transit drivers. Replacing or supplementing these drivers would likely result in high upfront costs but would likely provide substantial returns from the decreased operational costs. Such a shift in costs could enable these agencies to increase service provision and possibly decrease costs to customers.

One of the most significant impacts to transportation from automated vehicles is likely to be found in the planning arena. It is unknown to what extent the ability to commute via an automated vehicle will impact where people choose to live. It is possible that commuters will choose to live in areas with a long commute, such as an hour or more, if they can use that time to do other things like work instead of having to actively engage in driving. This has implications for how state and local governments plan for long-term land use.

Furthermore, in order for the safety benefits of automated vehicles to be fully realized, connectivity between vehicles (V2V) and between vehicles and infrastructure (V2I) will be needed. These connected vehicle systems provide automated vehicles with information that might not be available through sensor equipment alone. For example, V2V applications would allow a vehicle that is making a sudden braking maneuver to transmit that information to other vehicles behind it that might not otherwise be able to detect the impending slowdown. Similarly, roadway-based sensors in a V2I application might detect the presence of a pedestrian, about to cross a roadway, that is in the vehicle's sensory blind spot. Connected vehicle applications, and particularly V2I systems that require the installation of equipment within the right of way, would be largely dependent on government initiative and funding. Very few agencies have the funding available to invest in this sort of infrastructure, and many have not yet accounted for these types of technologies in their strategic planning and associated fund programming processes.

Potential Impact to Transportation Agencies

For state and local transportation agencies, automated vehicles have the potential to disrupt the focus of their mission. In the face of decreased funding, many state-level agencies are already turning their focus away from infrastructure development (in terms of building and maintaining roadways) and toward intelligently managing and operating those roadways with new technologies. Large urban areas are turning to technology-dependent integrated corridor management and active traffic management strategies in order to operate congested urban roadways. Smaller areas are increasingly able to use crowdsourced data from system users and private data from companies such as INRIX to manage and operate their road networks without the need to invest heavily in roadside monitoring equipment. It is possible that automated vehicles and connected vehicle systems will accelerate this shift in focus from roadway construction and maintenance to systems operations, technology management, and data-based service provision (*30*).

Immersive Interfaces

Technology users generally interact with their products through a traditional interface such as a monitor or other screen to view information and through a keyboard or touchpad for entering information and navigation of the device. This includes interfaces with vehicular systems, which are typically used through controls on the dash and may feature some sort of viewing screen imbedded in the dash. Immersive interfaces represent a transition from this traditional model to what might best be described as virtual reality (VR) environments.

Two important aspects of immersive interfaces are how the user receives information and how the user interacts to provide information back through the interface. Immersive interfaces generally provide information to technology users in one of three ways:

- **Visual**—Visual information can be presented in an immersive interface in any number of ways. Augmented virtual reality (AR) involves the computer generation and projection of information that is presented directly in the user's real-world environment. This might best be thought of as holograms or overlays. Similarly, VR involves the collection and addition of real-world data to a completely computer-generated environment. Users of a VR-based interface might wear a special device over their eyes that portrays the real world in a virtual environment.

- **Auditory**—Auditory information is fairly straightforward, but immersive interfaces can make use of three-dimensional audio that gives the listener the sensation of audio coming from different directions, creating a more realistic and information-rich environment.

- **Tactile**—Immersive interfaces can also provide tactile inputs to users. Using special equipment, the users of these types of interfaces operate within VR and receive tactile responses when interacting with virtual objects. For example, people interacting within a VR environment might touch a virtual object and would, through devices worn on their hands, receive the sensation of touching an object.

In terms of users interacting with the technology and providing information and feedback, immersive interfaces can accommodate the following options:

- **Gesture recognition**—Sensors detect body movement, such as that of the hands or eyes, and interpret that movement as input into the device. An example of this application is Kinect for Windows, which allows users to interact with the virtual world through body movements. Detail in gesture recognition has also increased with the use if infrared light-emitting diodes, which allow for fine-grained tracking of headsets and controllers in AR/VR devices.

- **Brain-computer interface**—Sensors interpret brain activity to carry out functions. These applications are increasingly being used in the medical field for patients who suffer from reduced mobility, such as quadriplegics.

- **Speech recognition**—These applications receive audio input directly from users, interpret that input, and execute commands based on that input. Apple's Siri, Amazon Echo, and Google Now all use this type of interface. This technology has advanced with the implementation of natural language processing. This form of language processing focuses on natural patterns of speech and dialects, working toward a seamless interface without the need for command words.
- **Omnidirectional treadmill**—This application allows users to interact with the virtual world by actually walking through it using a specialized treadmill that converts movement in the real world to movement in the virtual world.

Immersive interfaces provide a new medium in which to interact with technology. This has led to an increasingly large base of individual hardware/software manufacturers entering into research and development in the field, resulting in variation in how VR and AR might be disruptive. This has been reflected in the current lack of AR/VR products available to consumers, despite the large number currently under development. The growth in touch-screen-based interfaces, such as those used in smartphones and tablets, relative to the decline in more traditional interfaces that use physical buttons is illustrative of the potential disruptive nature of immersive interfaces.

Various VR and AR technologies have current consumer products or are in development with expected consumer products to be released within the following years. While many similarities exist between these developing technologies, the image fidelity, control schemes, and background head tracking systems differ. It is expected that within the next few years, market standards will emerge, allowing for broader market access for software developers.

AR headsets can be designed to operate alongside a computer or as mobile devices. Google Glass launched an AR device in 2013 that allows users to interact with Internet-based programs through a screen at the periphery of the right eye. Interaction is primarily through Google's natural language voice command system, but the device also had a simple touchpad on the right side. Concerns over the outward-looking camera have led Google to stop active development, and the company has opted to purchase Magic Leap as its new AR device (*31*). The Google Magic Leap (*32*) is a screenless AR device that projects AR images directly onto the user's cornea. The device appears to be primarily gesture controlled with a single home button on the headset (*33*). Microsoft's HoloLens (*34*) was expected to be released as a consumer product in the first quarter of 2016. Designed to operate with a personal computer running Windows 10, HoloLens is cordless, allowing the user to operate the device freely within range. It will function as an additional screen and could allow for conference calling, data visualization, and simple gameplay within projected holograph-type imagery. Control is a mix of voice command and simple gesture recognition. The device has built-in headphones, allowing for directional audio informing spatial awareness.

AR mobile apps and directional software that allow for pass-through AR are the most established software applications currently. They allow simple information to be tied directly to the user's location and adapt existing content to a new medium. An example of such an application would be one that allows users to pull up Wikipedia articles when looking at a historical monument (*35*) or to view the closest transit stations (*36*). Mobile pass-through applications use the camera on smartphones to layer digital information on top of a real-time image for users. The most established use of AR is the projection of traveling directions to drivers via the windshield of their vehicle. These systems are adapted from techniques used for military fighter pilot helmets, and there are now consumer-grade versions for motorcycle helmets (*37*) and automobile drivers (*38*).

Many of the technologies and applications that would make use of immersive interfaces are likely to find the greatest penetration in homes and businesses. Most developers are currently focused on using immersive interfaces in the area of entertainment, specifically video games. However, while video games are currently the key development platform for immersive interfaces, there are indications that these technologies could be leveraged for enhanced social interaction, as evidenced by Facebook's recent purchase and development of the VR device Oculus Rift. The potential for widely adopted and integrated VR/AR technology into current work flows could allow for a large increase in workers' ability to work remotely or in multiple smaller offices, reducing commute lengths. Immersive interfaces would be able to provide super-conferencing with high-quality video calling and would reduce the need for working in the same geographical location. Various visualization techniques are increasingly common in private architecture firms and more limited in construction, allowing for interaction with and manipulation of designs in a virtual environment. Immersive interfaces have also seen growing use in the medical field, providing improved doctor-patient interaction to the point that medical advice can be administered without the need for an in-office visit. One example of this is the company 2nd.MD (*39*), which has emerged as an online-based teleconferencing system allowing potential patients to have a preliminary medical review before meeting specialists. While the current system only allows patients to provide medical records to be reviewed, advancements in immersive interfaces would open up the potential for more exact diagnosis by specialists without the need and expense of meeting in person (*40*).

Applications and Implications

The scale and adoption of immersive interfaces will rely strongly on how consumer-grade products perform in the marketplace, which is unclear. However, for transportation, immersive interfaces have the potential to significantly impact how the driver interacts with in-vehicle systems. For example, heads-up displays would project information to the driver via the windshield of the vehicle, reducing the need to take one's eyes off the road while driving.

A significant issue with these types of applications is distracted driving. These types of immersive interface applications are potentially distracting to drivers because they draw attention away from the activity of driving.

The use of AR in vehicles, while holding the risk of distracted driving, may also increase the amount of new technology and sensors used in cars. This could potentially speed the development and availability of automated vehicles. For example, many vehicle AR technologies include software and sensors that can aid in recognizing listed speed limits, identifying lane position, and assessing distance between vehicles. These AR systems provide an avenue for auto manufacturers to introduce many of the required sensors and background programs required for autonomous vehicle implementation, helping adoption rates as autonomous vehicles make strides toward a consumer-grade product.

With the immersive interface technology still under development, most of the near-term applications from a governmental perspective involve using these devices for simulation, visualization, and training.

The National Aeronautics and Space Administration, for example, is using VR immersive interfaces to replace larger, more expensive training simulators with goggles and individual haptic feedback systems. For transportation, cheaper mobile and augmentable training simulations could have large impacts on emergency vehicle training, training for the trucking industry, and general driving education. Firefighters and police could benefit from situational simulations that provide training in standard and extreme scenarios at reduced costs. Transit drivers and emergency service providers could have new options at their disposal for training within a virtual environment, which could reduce the cost of more expensive simulation systems and hardware or of running empty buses on transit training routes.

Potential Applications by Transportation Agencies

There is a growing interest in the use of VR for visualization in urban design, construction, and public engagement. Urban design and public engagement use has been tied to recent trends in scenario planning and three-dimensional visualization software such as City Engine with initial porting of this software into VR headsets. This system can allow planning decisions such as transportation prioritizations, land use variations, and form base code alternatives to be visualized in illustrated buildouts at short-, medium-, and long-range increments. This can allow for better public understanding of impacts through a visual medium and in turn provide a more accessible medium for applicable input. Three-dimensional design practices can improve design and construction processes by allowing improved visualization of design build alternatives, which could reduce the cost of technological overhead. Furthermore, these applications could increase public participation in the transportation planning and development process through home use of these devices for virtual town halls. The ability of the public to visualize transportation policy impacts in a three-dimensional world could have significant implications for public outreach efforts associated with transportation projects.

Heads-up display applications, in particular, have the potential to significantly impact how agencies such as transit, firefighters, police, and postal carriers operate. When used in vehicles, these applications can allow for advanced navigation including computer reading of speed and instructional signage. They can be head mounted (such as through a helmet) or dash mounted. Heads-up display systems within transit can allow for new drivers to better access navigation systems with built-in instructions on stop locations and can provide drivers with information on route time. AR technology can also improve wayfinding and can facilitate dynamic trip reassignment. Immersive interfaces can provide a new avenue to access information that before was too unwieldy or fine grained to be accessible during specific tasks, potentially reducing the amount of time required to complete tasks or the need for a separate dispatcher.

The military has used AR in minimal applications on head-mounted displays for years, allowing fighter pilots to view vital information and direction on a helmet facemask. This same technology has the potential to provide information to drivers including hands-free wayfinding without the need to look away from the road, as with current GPS systems. When combined with route optimization, this could be an asset to emergency response vehicles, postal workers, and transit drivers whose routes vary day to day. The use of AR could reduce the demand for certain types of trips. For example, it is envisioned that VR technologies could reduce the need for some types of doctor's visits because it would allow for the remote examination of patients. Furthermore, immersive interfaces could continue to accelerate the trend of remote office locations, reducing the need for drivers to commute on a daily basis for work.

Conclusions and Policy Considerations

Disruptive technologies and technology applications have the potential to significantly impact how Texans travel and how Texas meets demands for that travel. This in turn has implications for transportation policy in Texas, and Texas statutes and legislation could hinder or enable these technologies. To address this, the research team conducted a review of state statutes to identify potential policy issues that might warrant future exploration as the technologies presented in this report continue to evolve. The research team identified five broad areas of policy concern for Texas to consider as it monitors and plans for advancements in these technology areas:

- Demand for roadway infrastructure.
- Privacy and data security.
- Safety.
- Standards
- State contracting and procurement.

Demand for Roadway Infrastructure

Many of the technologies and technology applications discussed in this report will likely change demand for roadway mobility if not the very model of personal mobility that has traditionally been founded on personal vehicle ownership. The MI makes it easier for travelers to access information on routes and travel times and to plan their trips accordingly. Many of these applications can be provided using third-party data sources and private service providers, potentially reducing the need for the state and local/regional entities to provide these services. This comes at a time when the IoT could potentially enable large-scale networks of sensors for the collection of data on state roadway operations and the remote monitoring of transportation assets, potentially reducing the costs associated with operating and maintaining the state's roadway network.

A potentially larger issue is to what extent Texans will be reliant on automobile travel in the future. The MI and immersive interfaces could significantly decrease the need for people to commute to their jobs because remote and even virtual offices will likely become increasingly popular. This would imply a decrease in demand for roadway capacity in the long run. However, the ability of citizens to use smartphones and other Internet-connected devices to access ridesharing services means that more mobility options are available outside of traditional alternate modes like transit, walking, or biking. Owning a personal vehicle is less of a requirement for personal mobility, which implies a potential increase in demand for roadway capacity. These issues raise questions about how infrastructure investment should occur in the future. Furthermore, there could be potential impacts to state transportation funding. If overall vehicle miles traveled decline due to a reduced reliance on personal automobile travel, then state and federal fuel taxes could decline. Furthermore, changes in vehicle ownership patterns could impact state- and county-level vehicle registration fees and state motor vehicle sales taxes.

Privacy and Data Security

Privacy and data security concerns have emerged as a key issue with the growth of MI access and the emergence of the IoT. Furthermore, automated vehicle technologies may rely on V2V communications and/or communication with roadside assets or cloud-based systems, which would result in significant data privacy and security concerns. Privacy and data use issues center on establishing protections around who can use the data and how data can be used. The current state code limits unauthorized use and possession of many types of data, restricts businesses on how they can share and use information, and establishes similar separate codes around digital medical information. In the future, new datasets containing personal data (such as driving tendencies, personal shopping choices, and frequent locations) may require an evaluation of laws regarding the protection of personally identifiable information.

From a security perspective, the risk of technology vulnerable to hacking becomes heightened with each new connected vehicle, transit vehicle, train, and airplane added to the transportation network, which is troublesome with the IoT and automated vehicle technologies. There are concerns among the public (and within the automotive industry) that automated systems, for example, could be hacked and control of the vehicle assumed by a party other than the driver. Similar concerns exist for the various Internet-connected equipment used by transportation agencies, such as ITS road sensors, traffic signals, and dynamic message signs. However, many of these issues are addressed through federal codes and specifically by the Federal Communications Commission.

Safety

Ensuring a safe and efficient transportation system is one of the primary objectives of the State of Texas when it comes to transportation infrastructure. Many technologies could result in significant improvements in driver safety. Automated vehicles have the potential to significantly reduce traffic accidents that are the result of human error. Advanced materials could lead to the development of more durable in-vehicle safety components or more flexible roadside structures that limit damage to vehicles and their operators during collisions. Furthermore, new immersive interfaces could lead to the wider deployment of facial recognition technologies that detect when a driver is fatigued or otherwise unable to safely operate a vehicle. However, many of these technologies could also reduce safety by potentially creating new distractions within the vehicle by creating new data interfaces for the driver. Policy makers at different levels of government may choose to address these new distractions through regulation. There is currently no state law limiting cell phone use while driving in Texas, but individual municipalities have established varying levels of cell phone and texting bans. Most of these bans are focused around cell phones and/or texting. As disruptive technologies including the MI and immersive interfaces continue to emerge, the issue of distracted driving may expand to include devices that are hands free, voice controlled, or gesture controlled.

Standards

Advanced construction materials could replace current materials used in routine pavement construction and rehabilitation on local, state, and national roadways. These materials may lead to the replacement of current AASHTO and federal design and materials construction standards that impact the construction industry. State procurement standards will be affected to accommodate advanced materials, which will alter life-cycle costs by initially increasing installation costs and reducing overall maintenance costs associated with signage, paints, coatings, bridge structural components, and pavements. Use of advanced materials could lead to the replacement of current methods for life-cycle cost analyses and replace assumptions on quality and cost considerations that relate directly to transportation procurement and project selection processes.

State Contracting and Procurement

New technologies may show strong potential to benefit the state, and in particular advanced materials could reduce maintenance and life-cycle costs. However, they are likely to carry a high cost in the near term, and the magnitude of potential maintenance and life-cycle costs is unknown. Therefore, these technologies might not be able to compete with existing goods, services, and practices in the traditional government procurement environment. The ability of disruptive technologies to compete in government bidding processes is currently controlled by several pieces of state code that outline the ability of state agencies to petition for the purchase of materials if no current competitor exists. Currently, material purchases may consider best value, which does allow for life-cycle costs to be integrated. While there is language in the state code stating that low-bid contracts are accepted once passed into competition, there is existing precedence for the encouragement of select materials.

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