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EMERGING TRANSPORTATION TECHNOLOGY PORTFOLIO

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Summary

In this document, we present the emerging transportation technology portfolio identified through internal literature survey and interviews with a subgroup of Texas Technology Task Force (TTTF) members and other technology thought leaders, conducted from September to December 2014. The team first identified and examined emerging technologies in areas of smart vehicle, sensing, computing, robotics, social networking, location-based service, manufacturing, energy, and materials, which are envisioned to reshape the transportation landscape in the short, middle, and long term. Seven key technology areas are included in the proposed technology portfolio, based on the inputs from subgroup interviews. For each technology area, we describe its scope, recent technology advances, market, and policy issues. We also synthesize qualitative and quantitative approaches to assess and manage the emerging technology portfolios and discuss how these approaches are applied in current context.

1. Background

Texas's 83rd Legislature passed the General Appropriations Bill, S.B. No. 1, Item 44, VII-31 and charged the Texas Department of Transportation (TxDOT) with examining and evaluating innovative transportation technologies to achieve cost savings, reduce traffic congestion, enhance safety, and increase economic productivity. As a result of this charge, the TTTF was formally created in 2013 to develop a vision for the future Texas transportation system that furthers the mission of TxDOT via technology-based solutions. TxDOT's mission is to provide a safe and reliable transportation system for Texas, while addressing congestion, connecting Texas communities, and becoming a best-in-class state agency.

In Phase I (February to August, 2013), the TTTF began with an internal core group that sought experts in various transportation technologies to provide directions for the Task Force. Three full-day workshops were held in Austin, on April 29, June 12, and July 13 of 2013. In each meeting, participants discussed emerging transportation technologies, their development stages, evaluation methods, and short- and long-term visions. The Phase I work resulted in the development and implementation of an evaluation framework for categorizing and selecting groups of emerging technologies and work plans for establishing a public-private consortium to further develop key emerging technologies and a work plan for developing test platforms for new transportation systems.

In Phase II (September to December 2013), the Task Force mainly focused on the background research pertaining to the strategic technology business plan, including a strengths/weaknesses/ opportunities/threats (SWOT) analysis, environmental scan, and vision and strategy development. The Phase II work resulted in a work plan and background research for completion and implementation of the strategic technology business plan in the next phases.

Phase III, i.e., the current phase, started in September 2014. The purpose is twofold: (1) review and revise past work; (2) expand the list of other highly potential technologies and/or integrated systems, and establish a transition plan for implementing and completing the strategic technology business plan. Between September and December of 2014, the research team conducted in-person and phone interviews with a subgroup of Task Force members, and determined an expanded list of emerging transportation technologies (i.e., technology portfolio) and a list of task force members. Section 2 summarizes this effort.

Built on subgroup interviews and literature survey findings, the purpose of this document is to provide an overview of emerging transportation technology portfolios and assessment and analysis framework. Sections 3 and 4 of this document address two areas: (1) synthesis of scope, trends, and qualitative benefit-cost appraisal of emerging technologies in the areas of automation/robotics, informatics, energy, and material, which are transformative to transportation systems (including surface, freight, and transit) in the broad sense; (2) a vision for the transportation technology portfolio analysis and management methods and their applications in current context.

2. Subgroup Interview

To identify emerging transportation technology portfolio, from September to December of 2014, in parallel to internal literature survey, the research team conducted six phone and in-person interviews with a subgroup of TTTF members from the last two phases and other technology thought leaders. The interviewees are technology thought leaders representing consulting firms, public agencies, and research institutes (see Table 1). A questionnaire was developed to streamline the interview conversations (see Appendix A). The questionnaire includes a table summarizing the key technology areas (newly added areas include smartphone applications, social networking, materials, energy, and manufacturing) and their emerging and potential applications identified through literature review. Using that table as a starting point, the interviewees provided their recommendations on three topics: 1) New technology areas worth looking into, e.g., unmanned aerial vehicles (UAV); 2) Specific technologies and/or technology applications, e.g., low-speed autonomous vehicles (AV); 3) Evaluation of technologies in a broader context, in terms of intermodal transportation (especially transit and freight), human behavior, land use, financing, insurance, and smart city management.

Table 1: Subgroup Interviewee List

Name	**Affiliate**	**Expertise Areas**
Steve Dellenback	Southwest Research Institute	CAV, UAV, smartphone applications
Mike Heiligenstein	Central Texas Regional Mobility Authority	V2I, roadway energy & materials, freight, parking, human behavior
Shelley Row	Shelley Row Associates LLC	CAV, TaaS, 3D printing
Harry Voccola	Nokia Location & Commerce	Freight, alternative fuels, CAV, big data
Michael Morris	North Central Texas Council of Governments	Freight, energy, CAV
John Betak	CAIT, Rutgers University	Freight, UAV, 3D printing
Darran Anderson	TxDOT	Transportation systems, technology
JD Stanley*	Cisco	Communications
CAV= Connected and/or autonomous vehicles UAV=Unmanned aerial vehicles *: Interview TBD	V2I = Vehicle-to-Infrastructure capability TaaS=Transportation as a service	

Synthesizing the subgroup interview inputs, the team updated the initial identified technology areas and developed the emerging transportation technology portfolio, by expanding the known technology areas, specific technology applications, and re-organizing the previous categorization. The team identified six primary technology areas and included in the portfolio four other technologies, as shown in Table 2.

Table 2: Emerging Transportation Technology Portfolio

	Technology Area	**Highlighted Applications**
Primary	AVs	Personal, freight, transit, rideshare
	Connected vehicles	Safety (e.g., wrong-way travel), TaaS
	Electric vehicle and systems	Smart grid, energy storage and transmission
	Cloud computing	Vehicular cloud computing
	Crowdsourcing	Surveillance and emergency management
	UAVs	Surveillance, logistics
Other	Location-based service	Rideshare, social network
	Google Glass	Virtual reality, Internet of Things
	3D printing	Distributed manufacturing
	Self-healing materials	Self-healing pavement

3. Emerging Transportation Technology Portfolio

In this section, we provide a synthesis of the scope, trends, applications, and barriers of each item in the technology portfolio provided in Table 2.

3.1 Autonomous Vehicles

AVs are vehicles capable of sensing the environment and navigating with limited-to-no human inputs [1][2]. There were two surges of AV developments. The first surge was driven by traditional car manufacturers, dating back to the 1980s (Mercedes-Benz robotic van). The second surge is driven by technology companies (for example, Google) starting from 2009–2010, and features high-resolution maps and artificial intelligence. Current AVs employ recent advances in areas including but not limited to sensing, computer vision, automated control, and artificial intelligence. AVs feature comprehensive use of various sensors, which include short- and long-range radar, Lidar (light detection and ranging), GPS, infrared sensors, and cameras. Table 3 provides a comparison of the applicability and limitations of these sensors. These sensors are used to collect environmental (including roadway, neighboring vehicles, and pedestrian), vehicle, and driver information in real time, which is processed by onboard computers to generate corresponding actions, such as automatic cruising, automatic braking, lane-keeping, warning of potential collision, automatic parking, etc.

Table 3: Environment-Sensing Technologies Used in AVs

Sensor	Range	Limitation
Laser (i.e., Lidar) detector	Generates constantly updated 3D map of car's vicinity	Low performance in adverse weather and with dirty (non-reflective) vehicles; low spatial resolution and slow scanning speed
Long-range radar	Detection range 150–250 meters, sees through fog	Price
Short-range (millimeter-wave) radar	Detection range 0.5–10 meters	Low spatial resolution, slow scanning speed, more expensive than laser-based sensor (but more robust in rain and fog)
Camera, i.e., video sensor	Can be used where visual information (e.g., lane marking, traffic sign, obstacle) plays a role	Less robust than short-range radar in foggy, night, or direct sunshine conditions. Requires more computing resources.
GPS	Navigation and routing	Public encoding—low resolution navigation
Infrared sensor	Senses proximity or motion based on infrared radiations	Inaccuracy, due to temperature-based working mechanism

The National Highway Traffic Safety Administration (NHTSA) (2013) categorized AVs into four levels of automation: L1—function-specific automation involving one or more specific control functions, or multiple functions operating independently; L2—combined function automation, involving at least two primary control functions to work together; L3—limited-self driving; L4—full self-driving.

The autonomous functionalities fall into categories of *safety-oriented* and *driver-assistance*. Safety-oriented features include collision avoidance, collision warning, automatic braking, blind spot warning, and driver monitoring. Driver-assistance features include adaptive cruise control (also known as "autopilot"), intelligent parking, and automatic reporting (e.g., OnStar) based on telematics.

AVs can impact various modes of transportation, including freight, transit, shared service, farming, and military; the primary mode influenced will be passenger cars. The Google driverless car was developed for and tested in urban and rural settings. In 2014, Google released a new driverless car prototype with a top speed of 25 mph, intended for urban and suburban settings rather than highways. As of 2015, many major car manufacturers (including GM, Mercedes-Benz, Volkswagen, Audi, Nissan, Toyota, Volvo, Tesla, and Google) have demonstrated AVs at various occasions, and announced plans to launch cars with partial autonomous features (L1 & L2), e.g., adaptive cruise control in stop-and-go traffic, to consumer market around 2015–2020, launching fully autonomous cars (L3 & L4) around 2020–2025. In freight transportation, automated convoying of trucks can contribute to fuel saving. AV-based shared mobility service (ridesharing or TaaS—Transportation as a Service) is another area attracting increasing attention, as it can complement the traditional public transit. In addition to these areas, AVs are also used in military and farming applications.

AVs can have immediate impacts on traffic safety (fewer vehicle and pedestrian collisions), driver experience (decreased stress related to driving and parking), mobility (smoother traffic flow and less congestion), and accessibility (for mobility-constrained groups), as well as long-term impacts on driver behaviors (e.g., vehicle miles traveled), land use, and related industries such as technology, manufacturing, insurance, and healthcare. Most existing studies are based on simulations involving hypothetical assumptions or stated preference studies based on traveler surveys. But since there are currently no large-scale deployment and field tests of AVs, the comprehensive impact of AVs is still an unexplored issue and characterizing it involves substantial uncertainties.

Several barriers prevent or delay the consumer market's adoption of AV technologies. The cost of full-fledged sensor system on an AV is still high (for example, Lidar system on Google's driverless car costs $70,000), although decreasing trends in the prices of technology products are often observed (in correlation with Moore's law, the price of information technology products, adjusted for inflation and steady increases in computing capacity, on average declined 16% per year from 1959 to 2009). Also, due to the dependence on sensors, satisfactory AV performance requires relatively good weather, light, and infrastructure conditions. Potential liability is another issue, considering the possibility of crashes involving driverless cars. This issue requires state-level and federal efforts on legislation and policymaking.

3.2 Connected Vehicles

Connected vehicles refer to vehicles equipped with communication devices that allow them to communicate with each other (V2V—vehicle to vehicle), to road side devices (V2I—vehicle to infrastructure), to personal mobile devices, or to the internet (vehicular cloud).

According to the underlying technology, connected vehicles can be categorized as cellular based or DSRC (dedicated short range communication) based [3][4]. The former uses the 3G or 4G cellular network, the same as smartphones. DSRC is a one-way or two-way short-range to medium-range wireless communication channel and corresponding set of protocols and standards dedicated for automotive applications (other short-range wireless communication protocols include IEEE 802.11, Bluetooth, and CALM). DSRC uses a 75-MHz spectrum in the 5.9-GHz range. Compared to cellular-based connectivity, DSRC features very low latency and high reliability. Its recommended use is to broadcast Basic Safety Messages at 10 times per second. Besides DSRC, other communication standards are permitted for non-safety-critical applications [5].

Connected vehicles underpin numerous transportation applications in the areas of safety, mobility (operations and management), and environment. Safety is a primary application, in particular for DSRC-based V2V and V2I systems. Safety applications envisioned include intersection collision warning, wrong-way travel warning, curve speed warning, red light violation warning, transit pedestrian detection, automatic incident reporting, forward collision warning, approaching emergency vehicle warning, vehicle safety inspection, rollover warning, highway-rail intersection warning, etc. The most significant mobility-oriented applications include Cooperative Adaptive Cruise Control, signalized intersection control, intelligent merge control, probe data collection, and emergency vehicle signal priority. Through connected vehicles, the information can be more effectively collected and disseminated, which enables TaaS and eco-driving. In addition, connected vehicles will allow more effective electric toll collection and road use measurement. Based on cellular connectivity, the applications cover real-time data, infotainment, safety diagnostics, and driver statistics.

The adoption of connected vehicles mainly faces a choice between DSRC and cellular technology, as both technologies are mature and inexpensive today. Policymaking is necessary to mandate the adoption of DSRC, as sufficient market incentives are lacking. Rulemaking concerning DSRC in the United States has been active since late 1990s. In 1997, ITS America petitioned the Federal Communication Commission (FCC) for allocation of the 5.85–5.925 GHz (i.e., 5.9 GHz spectrum) for DSRC. In 1999, the FCC allocated 75 MHz of spectrum in the 5.9 GHz band to be used by intelligent transportation systems (ITS). In 2003, the FCC adopted a report and order establishing licensing and service rules for DSRC in ITS radio service. In 2003, the USDOT announced the Vehicle Infrastructure Integration initiative. Nonetheless, in the last several years, due to the sparse actual deployment of DSRC device, the ITS community faces a "use it or lost it" situation in possessing the 5.9 GHz spectrum resource. In 2012, the FCC opened a Notice of Proposed Rulemaking (NPRM), on the revision of the commission's rules to permit unlicensed national information infrastructure devices in the 5 GHz band. In 2013, the National Telecommunications and Information Administration expressed concerns about the potential risks, and agreed with ITS America that further analysis is needed to determine whether and how the multiple risk factors can be mitigated. In 2014, the NHTSA issued an Advance NPRM to begin implementation of V2V communication technology (mandating DSRC on light-duty vehicles), and an NPRM is expected to be delivered by 2016. An overview of the DSRC rulemaking process is shown in Figure 1.

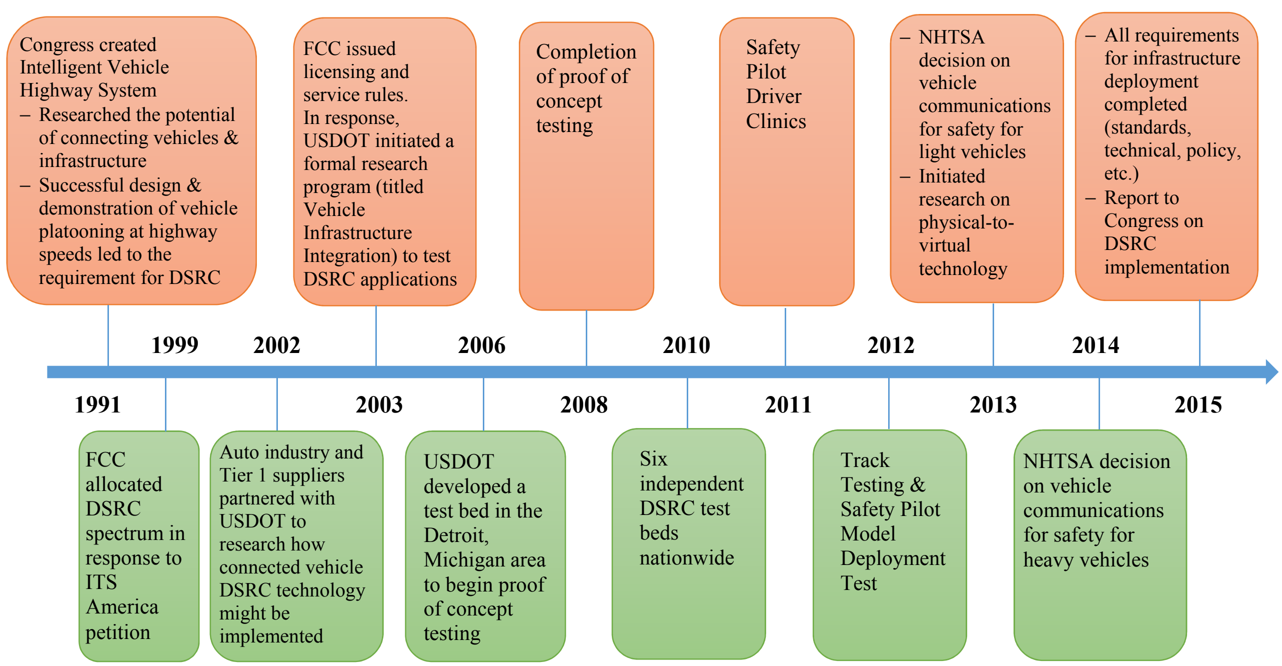

Figure 1: Rulemaking on DSRC (Adapted from tollroadsnews.com)

In contrast to the DSRC situation, in the last five years 3G and 4G communication architectures and devices have become mature, and cellular technology has drawn increasing attention, now applied in infotainment and subscription-based communications (e.g., OnStar) [13]. Car manufacturers, technology companies, and wireless carriers are all engaged in this area. Many car manufacturers are implementing or modifying the apps of Google and Apple in their cars. In 2013, Tesla connected all of its cars to the internet over 3G and 4G through AT&T's M2M (machine-to-machine) suite of applications, which is AT&T's Internet of Things platform. In 2013, GM switched its provider OnStar (OnStar provides emergency services and vehicle diagnostics and directions based on voice and data communication) from Verizon to AT&T for 2015 models, after partnering with Verizon for almost 20 years, partially due to the compatibility of AT&T's communication standards with other countries. As of September 2014, AT&T announced partnership with eight car makers, Verizon announced four, Sprint announced two, and T-Mobile announced one. In 2014, Google and Apple introduced their infotainment systems, respectively called Android Auto and CarPlay. Android Auto features audio and messaging, while CarPlay features Siri, Maps, and iTunes Radio.

Connected terminals will increase to 50 billion by 2015, among which 0.75 to 1 billion will be automobiles. Fusion of DSRC with cellular technology is possible and anticipated. In 2011, the GSM Association predicted that DSRC/WAVE (Wireless Access for Vehicular Environments) may be integrated into 4G to provide diagnostics and maintenance functions, through heterogeneous or "vertical" roaming and software-defined network (SDN). Many peer-to-peer wireless systems will likely interact closely with the 4G. DSRC/WAVE units are expected to utilize wireless backhaul to the cloud through cellular or dedicated wide area networks.

3.3 Electric Vehicles and Systems

Electric vehicles (EVs) are powered through a collector system by electricity from off-vehicle sources, or may be self-contained with a battery or generator to convert fuel to electricity. Broadly speaking, EVs include road and rail vehicles, surface and underwater vessels, electric aircraft, etc. [6][7]. EVs can be wirelessly charged, through a technology using electrodynamic induction. Electric systems include power storage, transfer, and distribution systems that support EVs. They include DC fast wireless charging stations along highways, wireless charging embedded in roadways, nano-batteries, solar highways, smart grids, and vehicle-to-grid (V2G) technology (vehicles are capable of directing electricity both from and to the grid).

Significant applications in this area include wireless charging and solar roadways. Electric wireless charging is most suited to transit, which has fixed route, range of travel, and stops. In the United States (e.g., Utah), Korea, and several European countries (the U.K., Italy, Germany, the Netherlands, etc.), some public transit systems have adopted wireless charging. Besides transit, market penetration of EVs in the personal car market is non-negligible. As of 2014, more than 600,000 highway-capable plug-in electric passenger cars and light utility vehicles have been sold worldwide, among which 356,000 are all-electric cars and 248,000 are plug-in hybrids. The United States is the market leader of EVs. Since 2008, 260,000 units of EVs have been delivered. A new Navigant Research report estimated that by 2023, EVs (including plug-in hybrid vehicles) account for 2.4% of U.S. auto sales. Solar roadways use photovoltaic pavement that can generate electricity by collecting solar power. Candidate locations of this technology include parking lots, foot paths, driveways, streets, and highways. Solar driveways and parking lots will allow charging of EVs with clean energy, and solar highways can allow charging while driving. These features will solve the notorious "range anxiety" issue associated with EVs. In addition, solar roadways can provide needed power and light after infrastructure-disturbing events such as earthquakes and tsunami, etc. Besides wireless charging and solar roadways, V2G is another noteworthy technology that has military applications and was used for emergency generators in the aftermath of the 2011 tsunami and earthquake in Japan.

Many benefits are envisioned with EVs and electric systems (wireless charging, solar roadway, V2G, etc.): EVs can mitigate the dependence on fossil fuels and reduce the environmental footprint of transportation. Barriers to widespread adoption include the cost of electric or hybrid cars, which is still higher than that of regular cars. In addition, zero or lower gas consumption means lower gas taxes. Therefore, to compensate for the lost tax revenues, seven states are charging or planning to charge a special fee to electrical vehicle drivers: Washington, Colorado, Nebraska, Virginia, North Carolina, and Wisconsin.

3.4 Cloud Computing

Cloud computing is the delivery of on-demand computing resources (everything from applications to data centers) over the Internet on a pay-for-use or subscription basis [8]. While the concept of cloud computing dates back to 1950s, it has rapidly developed in the last decade, when computing and communication architectures become mature. The primary aim of cloud computing is to cut costs and help the users focus on their core business instead of being impeded by IT obstacles. The National Institute of Standards and Technology identifies five essential characteristics of cloud computing: on-demand self-service, broad network access, resource pooling, rapid elasticity, and measured service. Cloud computing services can be categorized as Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS). See Figure 2 for the hierarchy in a mobile cloud computing architecture. In transportation, the most relevant concept is mobile cloud computing, which involves three layers in the architecture: application layer, platform layer, and infrastructure layer. Vehicular cloud computing is a particular type of cloud computing, which refers to "A group of largely autonomous vehicles whose corporate computing, sensing, communication and physical resources can be coordinated and dynamically allocated to authorized users," (Whaiduzzaman et al. (2014) [9]). The architecture of vehicular cloud computing is illustrated in Figure 3.

Aligned with the three-layer architecture of mobile cloud computing, applications of cloud computing in transportation fall into three categories: IaaS at the infrastructure level (e.g., data streaming and archiving on public or private cloud), PaaS at the platform level, and SaaS at the software level (e.g., smartphone apps). In last five years, research and development (R&D) activity on vehicular cloud computing has been very active. In 2011, IBM announced the IBM SmartCloud framework to support their Smarter Planet initiative. Among the various components of the Smarter Computing foundation, cloud computing is a critical piece. In 2011, Microsoft committed 90% of its $9.6 billion R&D budget to cloud computing. The Ford Motor Company combines social networks, GPS location, and real-time vehicular data to assist drivers using the cloud. Toyota and Microsoft also announced a $12 million partnership to bring cloud computing to Toyota. It is predicted that cloud applications will account for 90% of total mobile data traffic by 2018, compared to 82% at the end of 2013.

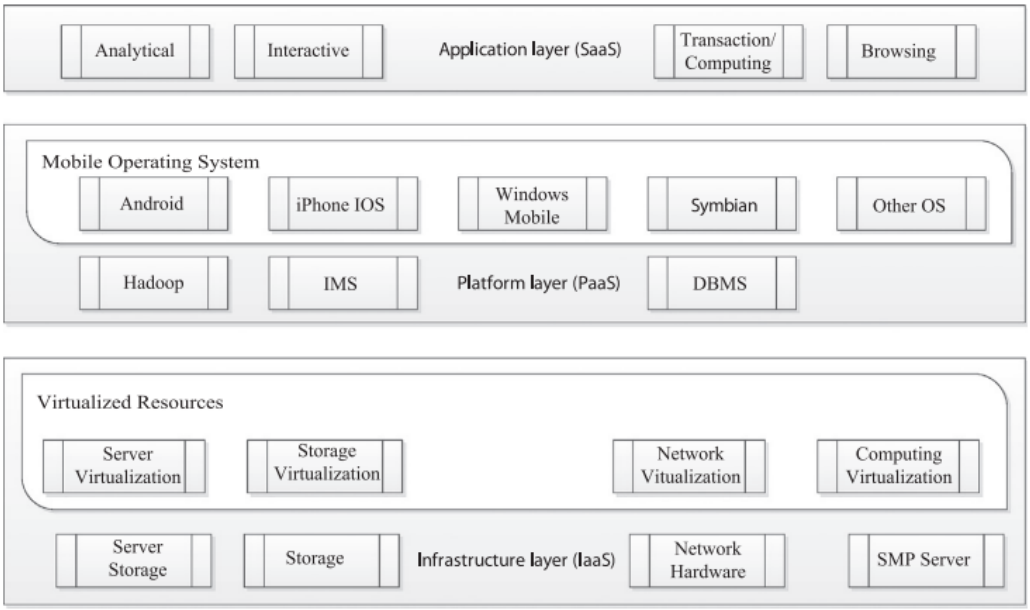

Figure 2: Mobile cloud computing architecture (Source: Dinh et al. (2011) [10])

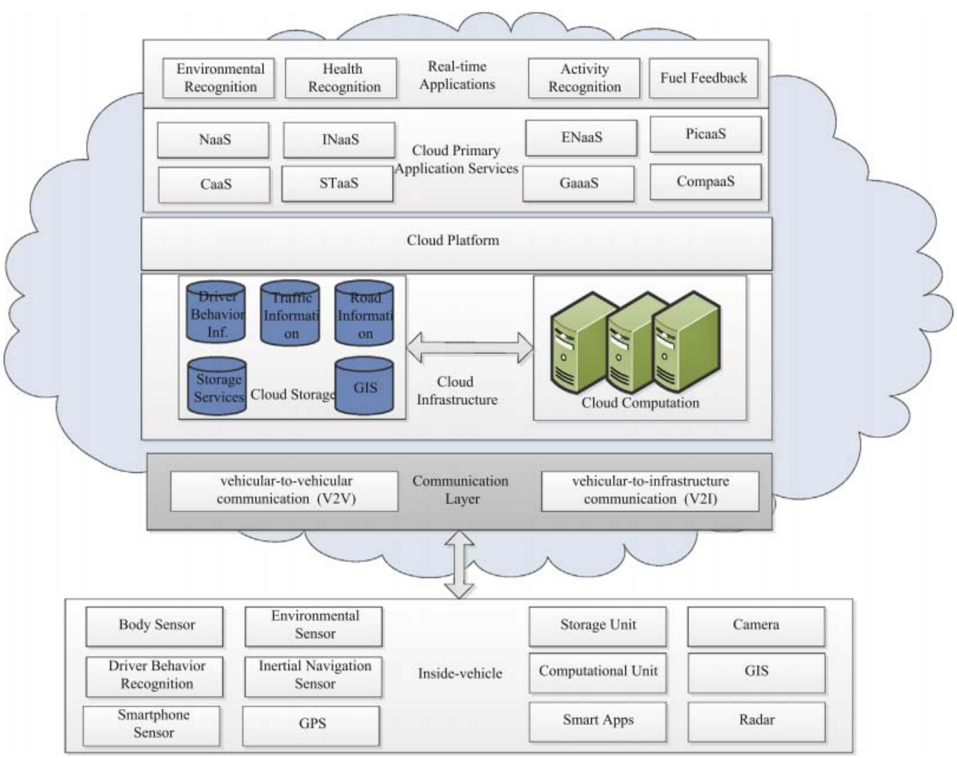

Figure 3: Vehicular cloud computing architecture (source: Whaiduzzaman et al. (2014), [9])

3.5 Crowdsourcing

Crowdsourcing is the process of getting information or funding, usually online, from interested individuals. In transportation, the smartphone is the primary platform, which enables mobile/location-based crowdsourcing. Outside the area of transportation, the crowdsourcing concept has been applied to analyzing the data of social networks and search engines. Examples include the Google flu prediction, geo-statistical analysis of Twitter data during Hurricane Sandy, and geo-spatial visualizations that identify residence and activity patterns.

Crowdsourcing technology has found broad applications in traffic data, transit, parking, road condition monitoring, and hazard monitoring [11]. Crowdsourcing has gained popularity as smartphones have become increasingly prevalent and now several successful commercial applications are based on the technology. In 2008, Waze Ltd. was founded. Waze is a crowdsourcing-driven GPS-based smartphone app. In 2013, Google bought Waze for $966 million, and added a social data aspect to its mapping business [12]. Google, Inrix, and Cellint are developing models for 'trading' information with traffic data consumers: consumers will launch an application on their smartphones that displays crowdsourced data about traffic flow in the area, and in return, their location information would be transmitted to the company for analysis. With the crowdsourcing technology, Cellint developed a different idea from Waze and Inrix. Their TrafficSense service looks into movement of signals from all smartphones within range of a cellular network. Cellular signal data is analyzed to generate speed, incident, and travel time information. TrafficSense can detect 99% of traffic slowdowns within a few minutes.

Several of the above mentioned companies are also working out similar agreements with public- and private-sector operators of vehicle fleets. Inrix has made agreements with auto companies, including Audi, BMW, Ford, and Toyota, to offer built-in computer connectivity in some car models. Inrix's data consists of 60% fleet data and 40% consumer data. The estimated traffic speeds are within 5 miles an hour of the actual speed 98% of time. The Inrix app offers routing, estimated arrival time, and warning of events and hazards. Inrix's data is used in Virginia and Massachusetts for travel time on dynamic message signs.

In addition to collecting traffic data, the crowdsourcing concept is being applied to public transit and road condition monitoring. Examples include Moovit (transit), Ototo (transit), Koozoo (parking and traffic), and StreetBump (road condition) [14]. In 2014, the Utah DOT released a crowdsourced road hazard (e.g., adverse weather) smartphone app.

3.6 Unmanned Aerial Vehicles

A **UAV**, also known as a drone, an unpiloted aerial vehicle, or a remotely piloted aircraft, is an aircraft without a human pilot aboard. There are two types of UAV: autonomous aircraft, and remotely piloted aircraft. UAVs are often preferred for missions that are too 'dull, dirty or dangerous' for manned aircraft. Related to UAV, an Unmanned Aircraft System emphasizes the other elements beyond an aircraft itself, including the UAV, control system, control link, and related support equipment.

UAVs are attracting increasing attention and related R&D activities have increased in the last several years. In 2007, DARPA (Defense Advanced Research Projects Agency) revealed a program to develop technology for a UAV with an endurance capability of over five years. In 2013, Amazon founder Jeff Bezos announced that Amazon was planning rapid delivery of lightweight commercial products using UAVs. In 2014, Google revealed it had been testing

UAVs in Australia for two years. The Google X program, known as "Project Wing," aims to produce drones that can deliver not only products sold via e-commerce, but larger delivery items. Of about 500 drone manufacturers worldwide, approximately one-third are based in Europe, which will create up to 150,000 jobs in Europe by 2050. U.S. manufacturers have about 60% market share. The global UAV market was valued at $6.762 million in 2014, and is expected to show robust growth, reaching $10,573 million in 2020. The compound annual rate growth is 7.73%.

Policymaking is underway concerning the civil applications of UAV, in both the United States and Europe. In 2013, the Federal Aviation Administration (FAA) selected six states to host test sites, emphasizing respective research goals. The six states are Alaska, Nevada, New York, North Dakota, Texas, and Virginia. In 2014, the National Transportation Safety Board issued a decision affirming the jurisdiction of the FAA to regulate UAVs. The FAA is expected to demand drone operators hold licenses and agree to flight limitation if the UAVs are used commercially. As of 2014, UAVs may only be flown by hobbyists for purely recreational reasons or by businesses that have obtained special FAA exemptions allowing commercial operations. To date, the FAA has issued only seven exemptions for commercial operations—all to movie production companies. The European Commission is keen to adopt a friendly-skies policy for the introduction of civil drones, which it sees as a great commercial opportunity. In the next 10 years, civil drones could make up an estimated 10% of aviation market, around 15 billion euros per year.

3.7 Other Technologies

Table 4 enumerates other technologies that may have significant impacts on future transportation.

Table 4: List of Other Emerging Technologies

Technology	**Applications**	**Barriers**
Location-based services: Program-level services that use location data to control features.	- Ridesharing: Uber and Lyft - Navigation: Waze - Incentive-based traffic management: Metropia - Tolling payment (as a substitute of traditional electronic toll collection): Xerox, 3M, and Q-Free	Regulation is needed for ridesharing apps. In some cities in the U.S., Europe, and China, multiple taxi driver protests against Uber and apps alike were reported.
Google Glass: Google Glass is a wearable technology that can display information in a hands-free format. Wearers communicate with the internet via natural language voice command.	- Released in March 2013 - Google Maps can be used - Has potential applications in healthcare and journalism	Security and privacy concerns; safety concerns while driving. UK and West Virginia have banned Google Glass in certain situations.
3D Printing: 3D printing (also called "additive manufacturing") refers to various processes for printing a 3D object. 3D printing allows mass customization, rapid manufacturing, and rapid prototyping. When combined with cloud computing, it allows decentralized distributed production.	- In 2005, home-use market was established with inauguration of RepRap project - Applications cover industrial design, automotive, GIS, and many others - In early 2014, Koenigsegg announced a supercar that utilizes many 3D printed components - Local Motors, Oak Ridge National Laboratory, and Cincinnati Incorporated are developing 3D printing for entire car body	Mass production capability is limited due to efficiency and cost-effectiveness.
Self-healing materials: Self-healing materials are a class of smart materials that have the structurally incorporated ability to repair damage caused by mechanical usage over time. [15]	- In 2013, TU Delft researcher demonstrated the potential of self-heading asphalt for repairing micro-cracks and extending service life of roadways in Netherlands	Large-scale field tests haven't been carried out, and cost-effectiveness is unknown.

4. Technology Portfolio Analysis and Management

Resource limitations require the organization to strategically allocate the available funding and labor to individual projects. Portfolio management is a tool to select the optimal set of technology projects.

4.1 Technology Life Cycle and Synergy

Table 5 summarizes the stages that each primary technology has reached. While technologies like crowdsourcing are mature and have underpinned commercial successes, other technologies are still in the stage of demonstration and deployment (initial). Surmounting the barriers in cost-effectiveness, liability, and other dimensions (e.g., privacy, and cyber security) calls for the collaborative efforts of engineers, policymakers, and manufacturers.

Evidently, these technology areas are not mutually exclusive, and a synergic trend is evident. For example, cars with both autonomous and connected features are anticipated, and the combined technology will bring further benefits. Detailed discussion of this effect will be presented in the strategic technology business plan.

Table 5: Development Stages of Emerging Transportation Technology Portfolios (2015)

	R&D	Demo	Deployment	Diffusion	Commercial Maturity
AVs	X	X	O	P	P
Connected Vehicles	X	X	O	P	P
Electric Systems	X	X	X	P	P
Cloud Computing	X	X	X	O	P
Crowdsourcing	X	X	X	X	O
UAVs	X	X	O	P	P
X: Completed; O: Underway; P: Pending.					

4.2 Technology Portfolio Management

A comprehensive technology-dimensional evaluation framework will be used to manage the full list of technologies by narrowing down the full technology portfolio into a shorter, critical list for further study. The use of such a framework is to be useful not only for comprehensive evaluation and understanding of the particular technologies but also for selecting and prioritizing which technologies to further focus on. The following provides a proposal for a tentative evaluation framework to apply to the technologies in the portfolio and is intended to be illustrative, as it will become refined based on Task Force guidance.

Four evaluations will be applied to assess technologies on the following four dimensions.

- Goal attainment: Ability to meet or further national and state transportation goals
- Barrier presence: Presence of barriers to adoption and implementation

- User group enhancement: Ability of technology to enhance or improve transportation user group experience
- Mode specific enhancements: Ability of technology to improve transportation by mode

For each evaluation, the research team and each Task Force member will be asked to rank technologies (columns) on each evaluation dimension (rows) on a scale from zero to five. Each integer on the ordinal scale will correspond to each individual's belief about how each dimension represents each technology, with lower values indicating less relevance in a dimension and higher values indicating more relevance. A key with dimensional ranking considerations will be provided (see Tables 6a–d for an example). In a Delphi-like process, each Task Force member will fill in a ranking for each technology-dimension intersection on each of the four matrices, and results from all members will be combined to form one final evaluation. An example set of matrices is provided in Tables 7a–d.

The final combined rankings will be used to inform a trade-offs analysis to compare technologies along common dimensions. Figure 4 illustrates an overview of the evaluation process. The final evaluation (radar chart within the spider chart) allows for the assessment and comparison of technologies along various dimensions.

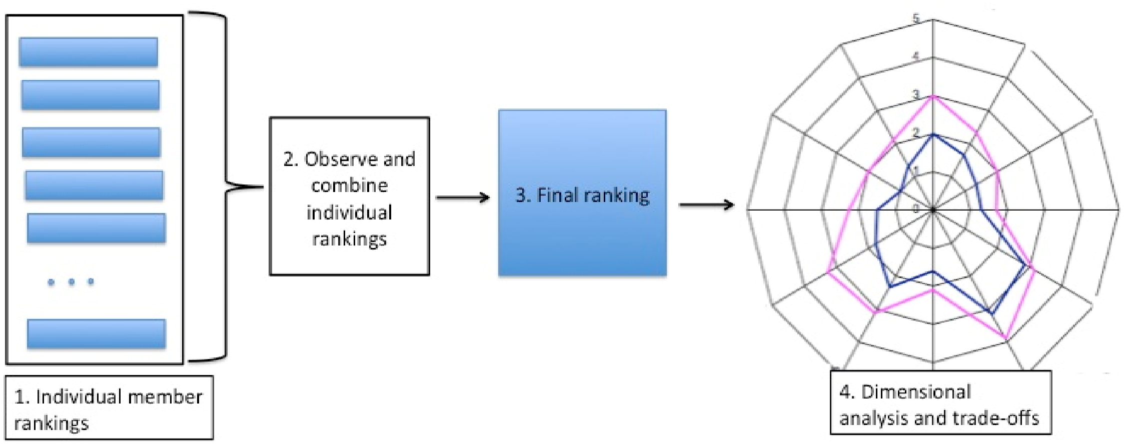

Figure 4: Overview of tentative technology evaluation framework

Technology-Dimensional Rankings Considerations

Table 6a: Example Factors Considered in Goal Rankings

Goal	Ranking Consideration
Safety	• Crash frequency reduction • Crash severity reduction
Congestion	• Decreased hours of congested travel • Improved traffic flows during congestion • Improved travel time reliability
Environmental sustainability	• Reduced fuel and energy consumption • Reduced air pollutant emissions, to meet EPA standards

Table 6b: Example Factors Considered in Barrier Rankings

Barriers	Ranking Consideration
Regulatory	• Legislative regulatory changes (may be helpful or necessary) • Administrative regulatory changes (may be helpful or necessary)
Cost	• Direct public agency costs
Safety	• New crashes or incidents otherwise avoidable • Increased crash or incident severity • Electronic security vulnerabilities

Table 6c: Example Factors Considered in User Group Enhancement Rankings

Enhancements	Ranking Consideration
User Cost	• Reduced operational cost • Reduced fuel cost
Safety	• New crashes or incidents otherwise avoidable • Increased crash or incident severity • Electronic security vulnerabilities

Table 6d: Example Factors Considered in Transportation Mode Enhancement Rankings

Enhancements	Ranking Consideration
Operational Cost	• Reduced fuel costs • Reduced labor cost
Safety	• New crashes or incidents otherwise avoidable • Increased crash or incident severity • Electronic security vulnerabilities

Technology-Dimensional Evaluation Matrices

Table 7a: Assessment of Ability of Technologies to Further National and State Goals

	AVs	**Connected Vehicles**	**Electric Systems**	**Materials**	**…**
Congestion					
Safety					
Environment					
…					

Table 7b: Assessment of Barriers to Technology Adoption

	AVs	Connected Vehicles	Electric Systems	Materials	…
Regulatory					
Safety					
Cost					
…					

Table 7c: Assessment of Impact from Technologies on System Users

	AVs	Connected Vehicles	Electric Systems	Materials	…
Freight (interregional)					
Freight (intraregional)					
Personal (commute)					
School/Student					
…					

Table 7d: Assessment of Impact from Technologies on Transportation Mode

	AVs	Connected Vehicles	Electric Systems	Materials	…
Highway					
Transit					
Bike/Pedestrian					
Aviation					
…					

5. Concluding Remarks

Now that the full list of prospective transformative transportation technologies in the portfolio has been developed based on subgroup interviews and literature survey findings, the next steps towards evaluation, prioritization, and promotion of critical technologies are described below.

The next task (Task 2) will see the reconvening of the full Task Force and the presentation of the technology portfolio to members. The research team will seek guidance regarding the specific technologies to pursue and the implementation of an evaluation framework for narrowing the technologies to the final critical technology list. The metrics and tables presented in the last section will be used as a starting point for the evaluation.

Task 3 will see the completion of Technology White Papers, which will contain complete in-depth research on identified critical technologies and core topics.

Task 4 will build on the previous three tasks and inform content for the completion of the Strategic Technology Business Plan, where comprehensive assessment of the critical technologies and their synergies will be performed, and the transition plan will be developed. Finally, for Task 5, the Task Force and the research team will develop an implementation plan that outlines the goals, priorities, recommendations, and strategies regarding transportation technology innovation and adoption in Texas for next steps.

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Appendix A. Subgroup Interview Questionnaire

I. Introduction to the purpose of the survey and objectives of the call/interview

This informal questionnaire/interview guide should be use to gain insight and facilitate ideas and discussion regarding technology research topics of top importance to the Texas Technology Task Force, the TxDOT Transportation Commission, TxDOT staff and policy makers, and Legislative Officials. Four objectives have been identified (listed below):

A. Obtain information and opinions on specific technologies from the interviewee that he/she believes will be important or transformative in each of the technology categories and for each of the transportation areas (listed in section II).

B. Inquire about which (if any) additional technology categories should be added or modified.

C. Identify gaps in expertise (based on the composition of last TTTF).

D. Identify who (if anyone) the interviewee would recommend as a Subject Matter Expert (SME) for missing expertise areas. If specific person is not known, identify where he/she would recommend looking (e.g., what company or organization would have staff that is an expert in that area).

II. List of specific questions that invite the interviewee to comment and discuss

A. Technology Specific: which technologies do you believe should have explicit focus in the next phase of TTTF work? Use the following categories and a guide to the discussion and for illustration of technologies.

   a. For each technology suggested, what is a supporting reason for including/focusing on it?

Technology Area	Examples for commentary
1. Autonomous Vehicle	Various levels of automation, automobile industry updates and advances, low speed autonomous vehicles, Policy and regulatory updates (federal, state, municipal)
2. Connected Vehicle	DSRC vs. Cellular based, Field tests and trials, Policy updates
3. Electric System	Smart grid, Electric vehicles, and also include other alternative fuels (CNG, solar, …)
4. Crowdsourcing and Mobile Cloud Computing	Waze, Moovit, HopStop, Ototo, Urban dynamics applications
5. Smartphone Applications	Rideshare, EnLighten, Insinc, Traveler Information, Demand induction, Tolling payment
6. Social Networking	Sentiment analysis, Geosocial networking, public relations, emergency preparedness, response and communications
7. Others (Materials, Energy, Manufacturing)	Nano carbon composite, Self-healing materials, Nano battery, 3D printing, dynamic traffic signals

b. Is the interviewee aware of new, disruptive trends and technologies in the following transportation areas:
   - Surface transportation
   - Transit
   - Freight
   - Ports, marine, waterway, and harbors
   - Air/aviation
   - Traveler information systems

c. Is the interviewee aware of new, disruptive trends and technologies in the following transportation-related areas:
   - Alternative financing (e.g., public-private partnerships)
   - City performance management (e.g., citizen engagement, open data portals, dashboards)
   - Land use (e.g., transit-oriented development)
   - Other

B. What additional, broad technology categories would the interviewee add?

   a. Include any justification for changes and additions.

C. Where are the gaps in expertise (based in composition of last TTTF)?

a. In addition, based on any added technologies or groupings that were not used in the past phases, is an added TTTF member needed to serve as SME for that technology?

D. Who would the interviewee recommend as a SME for that area? Or, if specific person is not known, where he/she would recommend looking (e.g., what company or organization would have staff that is an expert in that area).

III. Closing: next steps and follow-up with interviewee

Note: this section is an open discussion and left blank intentionally.