



**THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH**

0-6803-P2

Emerging Transportation Technologies White Papers

Volume 1: Autonomous Vehicle Technologies

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Peter J. Jin
Dan Fagnant
Andrea Hall
C. Michael Walton

TxDOT Project 0-6803: Technology Task Force

AUGUST 2013; PUBLISHED MAY 2015

Performing Organization:

Center for Transportation Research
The University of Texas at Austin
1616 Guadalupe, Suite 4.202
Austin, Texas 78701

Sponsoring Organization:

Texas Department of Transportation
Research and Technology Implementation Office
P.O. Box 5080
Austin, Texas 78763-5080

Performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.



**THE UNIVERSITY OF TEXAS AT AUSTIN
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0-6803-P2 Volume 1

**EMERGING TRANSPORTATION TECHNOLOGIES
WHITE PAPER: AUTONOMOUS VEHICLE
TECHNOLOGIES**

Andrea Hall
Dan Fagnant
Peter Jin
C. Michael Walton

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Introduction to Autonomous Vehicles

Autonomous vehicles sense their environment through technologies such as Lidar, video image recognition (computer vision), GPS, and radar [1]. These sensing capabilities may be combined with automated steering, braking, and acceleration, as well as navigation and routing systems, all of which enable the vehicles to navigate their environment with limited or even no human input in advanced implementations. In this way, the task of driving is shifted from the human driver to the car itself.

The adoption of these vehicles may offer benefits such as reduced traffic collisions due to elimination of human driver errors (including distraction, inattention, and aggressive driving) as well as greater system reliability and faster computer reaction times. Human failures (as opposed to those stemming from the vehicle or roadway environment) are the primary cause of over 90% of U.S. crashes [2], so this technology possesses the potential for substantial crash savings. Other potential benefits include smarter and greener driving and navigation, reduced urban parking needs due autonomous parking capabilities, and increased access to travel by occupants who face obstacles due to age or physical impairment. If autonomous driving capabilities are combined with communication between vehicles and/or infrastructure, other mobility benefits may also arise from applications like cooperative adaptive cruise control (tightly spaced road trains) and freeway traffic flow smoothing algorithms. When considering cooperative adaptive cruise control alone, freeway capacity nearly doubles with full market penetration, and substantial gains are realized even at lower penetration levels [3]. In short, the potential savings in human life, economic benefits, and reduced state expenditures for capacity expansion are quite substantial.

Levels of Autonomy (NHTSA and SAE)

In May 2013, the National Highway Traffic Safety Administration (NHTSA) issued a policy statement regarding autonomous vehicles, focused on three main areas: definitions of levels of autonomy; a national research plan; and recommendations to the states regarding the adoption of autonomous vehicles [4].

The levels of automation described below provide a summary of the NHTSA definitions.

Level 0: No automation. The driver is in complete and sole control of the primary vehicle controls (brake, steering, throttle, and motive power) at all times, and is solely responsible for monitoring the roadway and for safe operation of all vehicle controls. (Vehicles with V2V warning systems only would fit into this category)

Level 1: Functional-specific automation. Involves one or more specific control functions (e.g., adaptive cruise control, electronic stability control, dynamic brake support in emergencies). These controls do not work in unison.

Level 2: Combined function automation. Involves automation of at least two control functions that work in unison. The system can relinquish control with no advance warning and the driver must be ready to control the vehicle safely. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centering.

Level 3: Limited Self-Driving Automation. Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control.

Level 4: Full Self-Driving Automation. The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Drivers are not expected to continually monitor the roadway.

In contrast, the Society of Automobile Engineers (SAE) [5] has developed a similar set of definitions that were designed to be more specific and consistent with industry terminology. Table 1 provides an overview of the automation definitions by SAE with a comparison to NHTSA definitions on the left side.

Table 1: Levels of Autonomy (SAE compared to NHTSA definitions)

NHTSA level	SAE level	SAE name	SAE narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Backup performance of dynamic driving task	System capability (driving modes)
Human driver monitors the driving environment							
0	0	Non-Automated	the full-time performance by the <i>human driver</i> of all aspects of the <i>dynamic driving task</i> , even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	1	Assisted	the <i>driving mode</i> -specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	Human driver and system	Human driver	Human driver	Some driving modes
2	2	Partial Automation	the <i>driving mode</i> -specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	System	Human driver	Human driver	Some driving modes
Automated driving system ("system") monitors the driving environment							
3	3	Conditional Automation	the <i>driving mode</i> -specific performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> with the expectation that the <i>human driver</i> will respond appropriately to a <i>request to intervene</i>	System	System	Human driver	Some driving modes
4	4	High Automation	the <i>driving mode</i> -specific performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> , even if a <i>human driver</i> does not respond appropriately to a <i>request to intervene</i>	System	System	System	Some driving modes
4	5	Full Automation	the full-time performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> under all roadway and environmental conditions that can be managed by a <i>human driver</i>	System	System	System	All driving modes

State of Research and Practice

In 2004 DARPA's (Defense Advanced Research Projects Agency) Grand Challenge invited researchers, automotive manufacturers, and technology providers to demonstrate autonomous vehicle concept feasibility by navigating a 150-mile route. While no team

made it further than 7 miles, the following year five teams succeeded [6, 7]. This was followed by a 2007 DARPA Urban Challenge, which took place in a mock-urban environment and was completed by six teams [8]. Participants in this challenge had to perform a number of tasks and travel to several destinations, all the while obeying traffic regulations, dealing with fixed and moving obstacles, planning re-routing due to deal with close roadways, and overcoming other difficulties. Since this time, numerous manufacturers have entered the fray, with Audi [9, 10], BMW [11-13], Cadillac [13], Ford [14], GM, Mercedes-Benz [13], Nissan [15], Toyota [10, 16], Lexus [16, 17], Volkswagen [18], and Volvo [19] testing driverless systems. Other technology providers and auto parts suppliers have also joined in, including (but not limited to) Google [20], Bosch [21], Continental [22] and AutonomouStuff [23].

As of April 2013, *The Economist* notes that Google's fleet of autonomous Priuses and Lexuses have logged over 435 autonomously driven thousand miles on U.S. public roadways without a crash, though a backup "safety driver" was used in all instances [24]. Additionally, most road miles were likely not conducted during difficult conditions (e.g., night time, inclement weather, road construction, faded traffic markings, heavy pedestrian environments, etc.), so a true comparison of crash rates with conventional human-driven vehicles is not possible at this time. Google also appears to be the most ambitious provider, aiming to have a commercially salable autonomous vehicle by 2018 [25].

Other companies, including some of those previously noted, have also tested systems on public roadways, with varying degrees of automation. These applications have taken a number of forms, in addition to the personal vehicle concept that could act as an exact substitute for a human-driven vehicle. For example, a number of companies and researchers have experimented with cooperative adaptive cruise control road trains, often with the first vehicle being human driven, and the following vehicles piloted through communication with leading vehicles as well as in-vehicle automation controls. Leaders in these types of applications include Berkeley's PATH, the Netherlands' TU Eindhoven, SARTRE (Safe Road Trains for the Environment) and Volvo [26, 27]. SARTRE's road train example application is shown in Figure 1.



Figure 1: SARTRE's Road Train with 4 m (13 ft) Gaps and 90 km/h (56 mph) Speeds [28]

Another unique application involving autonomous vehicles is the EU's CityMobil2 driverless vehicle project [29]. This project seeks to deliver automated road transport in low-speed closed-system environments. One unique feature regarding the vehicles that will be deployed in these test applications is that the vehicles will truly operate autonomously, with no human driver present for even backup purposes. Figure 2 depicts two of the proposed vehicles to meet the project needs:



Figure 2: Proposed Vehicles by Robosoft (left) and Induct (right) for CityMobil2 [30]

Over the next 4 years, five cities throughout Europe will be selected for testbed demonstrations for 5- to 8-month demonstrations from among the following candidate cities:

- Reggio Calabria
- West Lausanne
- Leon
- CASA
- Vantaa
- Brussels
- La Rochelle
- Trikala
- Oristana
- San Sebastian
- CERN
- Milan

Additionally, a number of other demonstrations and projects have been conducted worldwide. A brief listing of other projects using autonomous vehicles conducted in the years since 2000 include but are by no means limited to the following [29]:

1. CyberCars
2. CyberMove

3. EDICT
4. NetMobil
5. CyberCars2
6. CyberC3
7. CityMobil
8. CityNetMobil
9. CATS

Readers who are interested in more information on the state of the practice regarding autonomous vehicles may be found by further reviewing these projects.

Academic, Industry, and National Research Efforts

With the emergence of autonomous vehicle and automation technology, new research efforts are required in order to understand the following:

1. How autonomous vehicles will change transportation,
2. How to harness the substantial benefits that autonomous vehicles might bring,
3. How to mitigate or avert potential negative autonomous vehicles consequences, and
4. How to ensure a smooth and orderly transition as autonomous vehicles enter the transportation system.

The fourth point may be further parsed, depending on how the technology evolves. Automation will likely continue to incrementally enter vehicles, so some action may be required to help smooth this process. However, it is possible that one or more provider may jump ahead and introduce Level 3 or even Level 4 autonomous vehicles in the near future (as Google hopes to do). Whichever path materializes, planning for and managing a smooth transition should result in much more favorable outcomes.

Within this overall framework, it is important to understand the most significant and active research areas. At the Transportation Research Board's Second Annual Workshop on Road Vehicle Automation, ten topic areas were identified. In each topic area, active research is taking place in the U.S. and around the globe, although much work remains to be completed [31]. The following list notes the topic areas identified:

1. Automated commercial vehicle operations
2. Cybersecurity and resiliency
3. Data ownership, access, protection, and discovery
4. Energy and the environment
5. Human factors and human-machine interaction

6. Infrastructure and operations
7. Liability, risk, and insurance
8. Shared mobility and transit
9. Testing, certification, and licensing
10. V2X communication and architecture

Given the above topics, it is clear that many have overlapping research areas, including areas that extend beyond automation functionality and are concerned primarily with vehicle communication. Additionally, several topics do not fall neatly into any of these categories, including paths for future autonomous vehicle market penetration, and incorporation of autonomous vehicles and their impacts into transportation planning models. Implementation and technology application questions for manufacturers and autonomous vehicle technology providers also remain, as even the most advanced prototypes are still undergoing testing.

In summary, these topics highlighted at the Road Vehicle Automation Workshop and identified in these added questions illustrate the current efforts that are taking place, as well as the future work that is still needed.

1. States with task forces or committees dedicated to autonomous vehicles or authorized legislation and licensing

As of August 2013, four states (plus Washington, DC) have passed legislation enabling autonomous vehicle legislation, eight have pending legislation under consideration, and six states (including Texas) have drafted legislation that failed [32]. In the Texas case, HB 2932 was referred to the House Transportation Committee, though it has not progressed from this point [33]. Figure 3 illustrates current legislative activity regarding enabling language for autonomous vehicles.

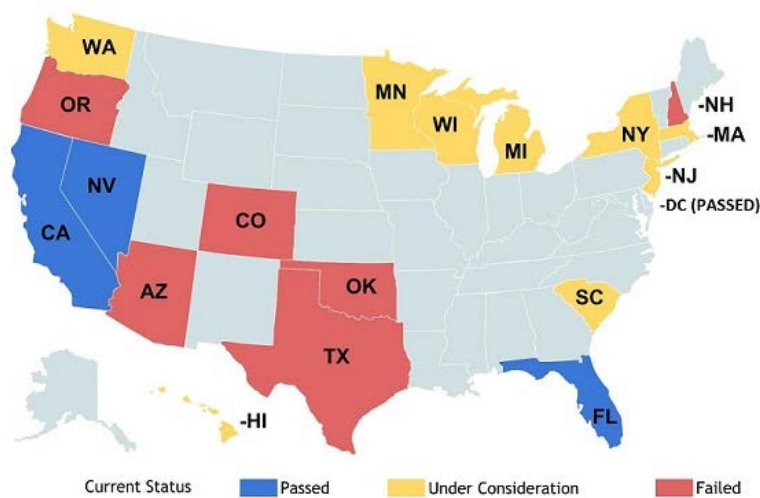


Figure 3: State Autonomous Vehicle Legislative Efforts [32]
 (Note: Michigan has since Passed Enabling Legislation)

Table 2 provides a more detailed view of individual state actions and lists the specific state bills that have passed, failed, or are currently under consideration. Table 2 also includes reporting dates for when bill language directs their respective state departments of transportation (DOT) or departments of motor vehicles (DMV) with developing details for autonomous vehicle licensing and other necessary regulatory efforts. Years shown in parentheses were proposed but no longer applicable since the corresponding legislation failed.

Table 2: State Autonomous Vehicle Legislative Efforts [32]

State	State Bill	Status	Reporting Date
Arizona	HB 2167	Failed	(2015)
California*	SB 1298	Passed	2015
Colorado	SB 13-016	Failed	(2018)
Florida*	SB 52	Passed	2014
Hawaii	HB 1461	Under Consideration	2015
Massachusetts	HB 3369	Under Consideration	2015
Michigan*	SB 0169	Passed	2016
Minnesota	HF 1416, HF 1580 & SF 1270	Under Consideration	2014
Nevada*	SB 313	Passed	Took effect March 2012
New Hampshire	HB 444	Failed	(2013)
New Jersey	S2898	Under Consideration	-
New York	S4912 & A7391	Under Consideration	2015
Oklahoma	HB 3007	Failed	-
Oregon	HB 2428	Failed	-
South Carolina	HB 4015	Under Consideration	2015
Washington	HB 1439 & HB 1649	Under Consideration	2026
Washington, D.C.	B19-0931	Passed	-
Wisconsin	SB 80	Under Consideration	-

*Allows testing.

2. California and Nevada’s Legislative Efforts

It is worthwhile to examine the prior efforts regarding autonomous vehicle enabling legislation from other states before Texas pursues such measures itself. Nevada and California were the first two states to pass such legislation and a comparison between the two efforts is enlightening.

First, it should be noted that the legislation from both states put the major onus of work on their respective DMV and DOT. That is, the enabling legislation coming from these states provides mandates that their state agencies develop the requirements that are necessary in order to allow autonomous vehicles licensing, as well as requirements for provisional testing. How the two states get to that point, however, differs significantly: Nevada’s legislation contains a mere 23 lines of definitions and broad guidance to its

DMV (though other general provisions were later added to state code by Nevada's DMV) [34], while California enacted a more comprehensive six-page bill [35].

Nevada's current regulations allow testing on public roads for all autonomous vehicle technology providers that are able to meet their standards. Google, Audi, and auto parts supplier Continental have obtained testing licenses in the state [22]. Nevada's requirements mandate that all applicants first provide proof of at least 10,000 miles of autonomous operation, along with a report and summary statistics. Licensees must ensure that at least two licensed drivers are physically present in the autonomous vehicle during testing, familiar with the autonomous vehicle's capabilities, and prepared to take over if necessary. At the department's discretion, licensing may be limited to any number of environments, including interstate highways, state highways, urban environments, complex urban environments, residential roads, unpaved or unmarked roads, as well as other potential restrictions for night driving, rain, fog, snow and ice, and high crosswinds.

California's legislation is more detailed, although final regulations for licensing are still under development and expected by 2015. This legislation includes added requirements for testing on public roads, including insurance requirements, the ability to quickly engage manual driving, failsafe systems, and sensor data storage and retrieval in the event of a crash [36]. The DMV must consider a number of regulations, including the total number of autonomous vehicles on California's public roads, licensing requirements for persons using autonomous vehicles, and procedures for denying and revoking licenses. Finally, the legislation requires public hearings and directs the DMV to enact strict autonomous vehicle oversight.

3. Preparing Texas for Autonomous Vehicles

In May 2013, the NHTSA released a policy statement providing guidance to the states regarding the permitting of testing of automated vehicles. This statement recommends against states authorizing the operation of self-driving vehicles for purposes other than testing at this time. The report authors note that technological and human performance issues remain, and assert that self-driving technology has not yet demonstrated the safety capability necessary for use by the public for general driving purposes. The policy statement also notes that this consideration may be lifted in the future as the technology is further tested and continues to improve, while also providing guidance for states wishing to pass enabling legislation and regulation to allow testing of autonomous vehicles on public roads. As such, this report recommends that Texas consider passage of legislation and accompanying regulations to allow the testing of autonomous vehicles on public roadways. If this action is pursued, this report strongly recommends that the following recommendations outlined by the NHTSA in their policy statement be followed.

Licensing Program

If testing of autonomous vehicles is to be enabled, Texas should develop a driver licensing program that would provide a driver's license endorsements (or separate driver's licenses) that authorizes the operation of self-driving vehicles.

The issuance of a driver's license endorsement (or separate driver's license) to a person should be conditioned upon certain prerequisites, such as that person's passage of a test

concerning the safe operation of a self-driving vehicle and presentation of a certification by a manufacturer of self-driving vehicles (or the manufacturer's designated representative) that the person has successfully completed a training course provided by that manufacturer (or representative), or a certification by that manufacturer (or representative) that the person has operated a self-driving vehicle for a certain minimum number of hours. As used here, "manufacturer" includes a company that alters a vehicle manufactured originally by another company in order to give it self-driving capability.

The training course should be submitted to the state agency that issues driving licenses for approval prior to the taking of that course by any person seeking a driver's license endorsement certification. The course should include providing an understanding of the basic operation and limits of self-driving vehicles, and knowledge of how to resume control of such a vehicle in the event that it cannot continue to operate automatically.

On-road Testing of Self-driving Vehicles (Minimizes Risks to Other Road Users)

Regulations for self-driving vehicle testing should include provisions to ensure that businesses testing such vehicles conduct their testing in a way that minimizes risks to other road users, including provisions such as these:

- Requiring businesses to certify that the vehicle has already operated for a certain number of miles in self-driving mode without incident before businesses seeking the license can test the vehicle on public roads.
- Requiring these businesses to submit data from previous testing involving the technology.
- Requiring businesses to submit a plan to the state regulatory body describing how the business plans to minimize safety risks to other road users. The plan could include training for test drivers employed by the business seeking to conduct the testing, fail safes in the design of the prototype automated vehicle, and/or aspects of the testing plan designed to ensure that risks to other road users are minimized.

The NHTSA strongly recommends that states require that a properly licensed driver be seated in the driver's seat and ready to take control of the vehicle while the vehicle is operating in self-driving mode on public roads.

Limited Testing Operations to Roadway, Traffic, and Environmental Conditions Suitable for the Capabilities of the Tested Self-Driving Vehicles

As part of the testing plan, self-driving vehicle manufacturers inform the state of the operating conditions in which they wish to test. Manufacturers wishing to test self-driving vehicles should be required to supply states with test data or other information to demonstrate that their self-driving vehicles are capable of operating in these conditions with limited driver intervention.

Appropriate limitations on the conditions in which a vehicle may be operated in self-driving mode should be considered. Regulations governing self-driving vehicle testing

should be tailored to limit the use of the self-driving mode to conditions conducive to safe operation in that mode.

Regulations governing self-driving vehicle testing could limit testing to the operating conditions for which the self-driving system is specifically designed such as driving on a limited access highway. Likewise, depending on the self-driving vehicle, regulations could limit testing of the self-driving vehicle to roads in only certain geographical locations, e.g., those known for having light traffic or for having heavy traffic at low travel speeds.

Establish Reporting Requirements to Monitor the Performance of Self-Driving Technology during Testing

To expand the body of data and support research concerning self-driving vehicles, businesses testing self-driving vehicles should be required to submit to the state certain information, including

- Instances in which a self-driving vehicle, while operating in or transitioning out of self-driving mode, is involved in a crash or near crash; and
- Incidents in which the driver of one of their self-driving vehicles is prompted by the vehicle to take control of the vehicle while it is operating in the self-driving mode because of a failure of the automated system or the inability of the automated system to function in certain conditions.

Other Recommendations

In addition to the NHTSA's recommendations regarding the licensing of drivers to operate autonomous vehicles for testing, and recommendations regarding autonomous vehicle testing, the NHTSA provides four recommendations for basic principles for testing of self-driving vehicles [4]:

- A. Ensure that the process from self-driving mode to driver control is safe, simple, and timely.
- B. Self-driving test vehicles should have the capability to detect, record, and informing the driver of malfunctions in the system of automated technologies.
- C. Ensure that installation and operation of any self-driving vehicle technologies does not disable any federally required safety features or systems.
- D. Ensure that self-driving test vehicles record information about the status of the automated control technologies in the event of a crash or loss of vehicle control.

Conclusion

Autonomous vehicles and automation capabilities show great promise for enhancing safety and land use savings (through reduced parking needs) and decreasing congestion and energy consumption, as well as indirect benefits, such as the reduced need for new road capacity expansion. Other states are pursuing efforts in this direction and the

technologies will continue to progress with or without efforts conducted on behalf of the state of Texas. Nevertheless, substantial opportunity may be gained through Texas' involvement. Texas boasts significant population, resources, land area, a business-friendly environment, and a growing economy. By harnessing Texas' strengths, the state of autonomous vehicle technology may be further developed, allowing Texas to economically benefit from the creation of private-sector jobs within the state, as well being quicker to realize the benefits that autonomous vehicles may bring.

To these ends, three major avenues may be pursued as follows:

1. Enable licensing procedures to allow autonomous vehicle testing on public roads – Multiple states have considered or are considering licensing of autonomous vehicles for testing purposes. Texas may pursue similar efforts, drawing on the experience of others, as well as NHTSA's recommendations.
2. Conduct one or more pilot programs – The EU's CityMobil2 program is one example of an autonomous vehicle pilot project that has the potential to greatly further the state of the technology. Pilot programs like this may be pursued with a more *Texas* bent.
3. Fund autonomous vehicle research – Much research remains to be done in order to harness the substantial benefits of autonomous vehicle technology and provide a smooth transition while avoiding potential pitfalls. Texas could fund such research efforts and become a leader in the field.

Each of these actions may be pursued individually or in combination in order to further the state's ultimate objectives of developing a prosperous economy while reducing the loss of life on Texas roads.

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**THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH**

0-6803-P2 Volume 2

**EMERGING TRANSPORTATION TECHNOLOGIES WHITE
PAPER: CONNECTED VEHICLE TECHNOLOGIES**

Peter Jin
Andrea Hall
Dan Fagnant
C. Michael Walton

TxDOT Project 0-6803: Technology Task Force

AUGUST 2013

Performing Organization: Center for Transportation Research The University of Texas at Austin 1616 Guadalupe, Suite 4.202 Austin, Texas 78701	Sponsoring Organization: Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080
Performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.	

Background

Connected vehicle (CV) technologies use wireless communication technologies to establish connectivity among vehicles and/or vehicles to infrastructure such as a cell tower or roadside communication equipment. The connectivity is classified into three types: V2V (vehicle to vehicle), V2I (vehicle to infrastructure), and V2X (vehicle to others, such as other personal devices, pedestrians, etc.). Figure 1 demonstrates several types of connections.

Currently, two major communication technologies are used in CV technologies. The first category is the local CV technologies based on DSRC (dedicated short range communication) (CV-DSRC). This type of technology establishes connectivity among vehicles through Wi-Fi, which uses wireless communication technologies (similar to radio but on a dedicated spectrum) to broadcast the vehicle information such as position and speed to surrounding environment [1]. The development and implementation of CV-DSRC technologies are primarily lead by the US Department of Transportation (USDOT)'s Research and Innovative Technologies Administration (RITA) and the National Highway Traffic Safety Administration (NHTSA). The second category is based on cellular telematics (CV-cellular), primarily used by the auto industry, IT companies, and cellular carriers. CV-cellular technologies are on the existing global cellular communication network such as AT&T and Verizon. Those technologies have been actively explored and developed in industry in parallel with the government-lead efforts on CV-DSRC technologies.

The term “connected vehicle” includes both cellular- and DSRC-based connection. Due to the significant technical differences and the resulting policy and administrative perspectives, in this white paper, we separate the discussions of CV-DSRC and CV-cellular to provide clear and meaningful perspectives on the current state of technology development and the strategies for implementation in Texas.

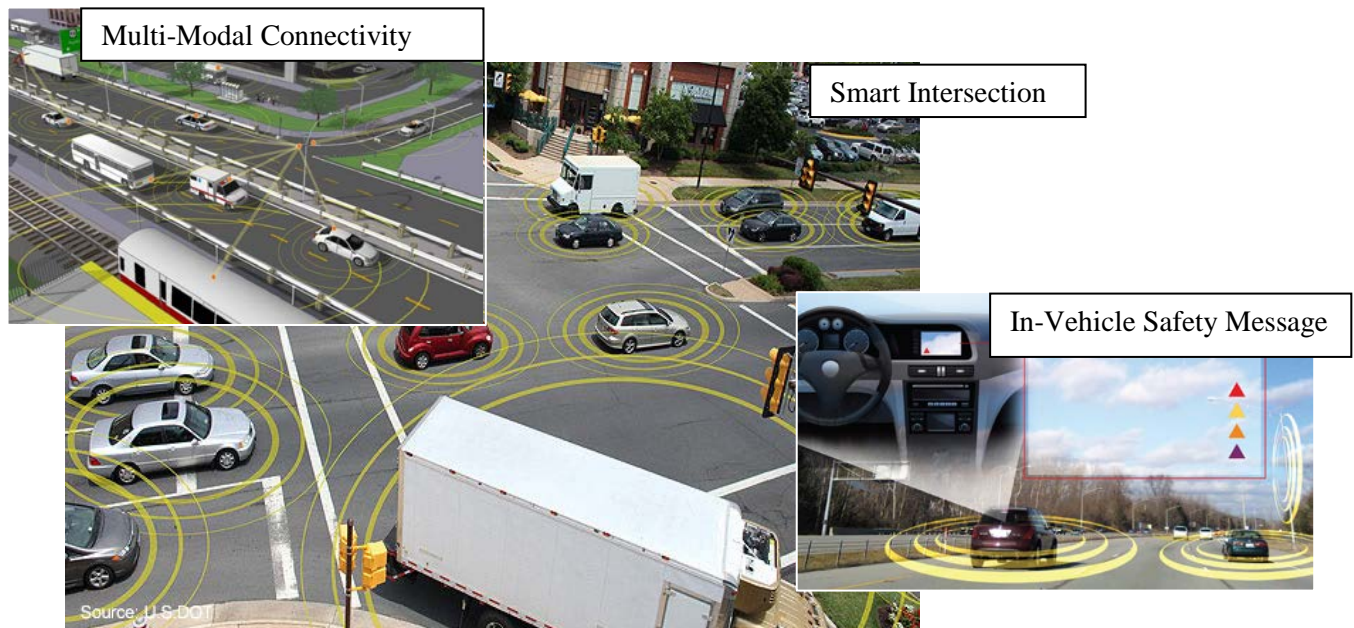


Figure 1. Connected Vehicle Technology Demonstrations

CV Technologies based on DSRC (Dedicated Short Range Communication)

1. Introduction

DSRC-based CV (CV-DSRC) technologies establish local V2V and V2I connectivity through DSRC, a short-range communication technology similar to Wi-Fi and Bluetooth. When fully implemented, the localized small-scale network can be merged into a CV communication network of a size comparable to today's cellular communication networks [2]. The potential applications based on this vehicular network are limitless. Lead by the USDOT and the NHTSA, the current development of CV-DSRC technologies prioritizes the active V2V and V2I safety applications that are expected to be the ultimate game-changers in meeting the national goal of "zero fatalities." Those applications may potentially address four out of five crash scenarios involving unimpaired vehicles. To achieve such a goal, vehicles will send electronic data messages, receive messages from other vehicles through the DSRC network, and translate them into safety warnings to drivers regarding specific hazardous scenarios [1]. Such hazards may include an impending collision at an intersection with limited visibility, a side-swiping collision with lane-changing vehicles in another vehicle's blind spot, or a rear-end collision with a stopped vehicle.

DSRC has several unique features suitable for vehicular applications. It is a two-way short- to medium-range wireless communication technology capable of transmitting messages at 5.9GHz. In Report and Order FCC-03-324, the FCC (Federal Communications Commission) allocated and licensed the 5.9GHz spectrum (75MHz bandwidth) for use by ITS (Intelligent Transportation Systems) vehicle safety and mobility applications [3]. The technologies have fast network acquisition, low latency, high reliability, and interoperability, making them especially suitable for active safety and mobility applications. DSRC works in high vehicle speed mobility conditions and is immune to extreme weather conditions such as rain, fog, snow, etc.



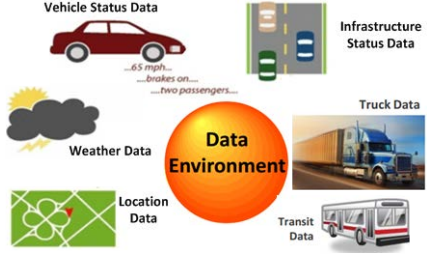


The CV-DSRC system consists of in-vehicle devices, roadside devices, backend communication, data, and security support systems. DSRC can be embedded during the manufacturing process, added as an aftermarket devices, and—at minimum—installed as basic vehicle communication devices that only provide only basic safety messages. Roadside devices also take several forms, such as DSRC roadside equipment (RSE), SPaT (signal phase and timing)-enabled traffic signal controllers, curve speed warning, data offload, and security gateway, etc. CV-DSRC requires significant back-end supporting infrastructures, especially the security network that validates and distributes the DSRC certificates. Such networks ensure the integrity, consistency, and extendibility of CV-DSRC applications. CV-DSRC can also potentially serve as a moving-sensor network that can provide real-time traffic flow, incident, and road weather information for use in advanced traveler information and traffic management systems. Such data functionality can be facilitated by the back-end data collection, communication, and dissemination systems [1].


2. Connected Vehicle Applications

CV-DSRC technologies facilitate a large variety of safety, mobility, and environmental applications (Table 1). Through V2V and V2I information communication, CV-DSRC can help increase the situational awareness of drivers and reduce or eliminate crashes with driver advisories, driver warnings, and vehicle and/or infrastructure controls. CV-DSRC may address

up to 82% of crash types with unimpaired drivers and may help prevent tens of thousands of crashes every year [3]. CV-DSRC mobility applications are facilitated by the data in V2V and V2I communication. The data allows efficient monitoring of mobility conditions and also facilitates microscopic, customized, dynamic, and multi-modal traffic management strategies and technologies. CV-DSRC data also enables environmental applications such as informing travelers about congested routes, alternate routes, and public transit to make their trip more fuel-efficient and eco-friendly.

Table 1. CV-DSRC Applications [1, 4]

Category	Applications	Examples
V2V Communications for Safety	<ul style="list-style-type: none"> • Forward collision warning • Emergency electronic brake light • Intersection movement assist • Blind spot warning/lane change warning • Left turn across path/opposite direction • Do not pass warning 	
V2I Communications for Safety	<ul style="list-style-type: none"> • Red light violation warning • Curve speed warning • Stop sign gap assist • Stop sign violation • Railroad crossing violation warning • Spot weather impact warning • Oversize vehicle warning • Reduced speed/work zone warning • Pedestrian warning for transit vehicles • Smart roadside 	
Real-Time Data Capture and Management	<ul style="list-style-type: none"> • Data elements: travel time, speed, flow, queue length, turning percentages • Performance measurement • Predictive variable message signs • Flow-optimized lane and speed control 	
Dynamic Mobility Applications	<ul style="list-style-type: none"> • Integrated Dynamic Transit Operations (IDTO) • Intelligent Network Flow Optimization (INFLO) • Multi-Modal Intelligent Traffic Signal System (M-ISIG) • Response, Emergency Staging and Communications, Uniform Management, and Evacuation (R.E.S.C.U.M.E.) • Enable Advanced Traveler Information System (EnableATIS) • Freight Advanced Traveler Information System (FRATIS) 	
Road Weather Management	<ul style="list-style-type: none"> • Enhanced maintenance decision support system • Information for maintenance and fleet management systems • Variable speed limits for weather-responsive traffic management • Motorist advisories and warnings • Information for freight carriers • Information and routing support for emergency responders 	

Category	Applications	Examples
USDOT program AERIS (Applications for the Environment: Real-Time Information Synthesis)	<ul style="list-style-type: none"> • Dynamic low emissions zone • Dynamic eco-lanes • Eco-traveler information • Eco-signal operations • Eco-ICM (integrated corridor management) • Support for alternative fuel vehicle operations 	 <p>The graphic features the text 'Green Driving' in green at the top. Below it, a blue car is shown from a side profile, emitting yellow signal waves towards a traffic light on the right. To the left of the car is a green recycling symbol.</p>

3. USDOT Vision

In 2010, the USDOT established a focused research agenda towards a “connected transportation environment” in which V2V and V2I communications and applications were envisioned. The national research efforts are currently lead by the USDOT’s RITA and the NHTSA. Previous research efforts on vehicle infrastructure integration and IntelliDrive have paved way for the development of CV-DSRC technologies and applications [4]. After years of pilot research and field tests, CV-DSRC is currently meeting two NHTSA critical decision points (illustrated in Figure 2). The first one is the expected enforcement of DSRC devices on all light vehicles in December 2013; the other is the enforcement of DSRC on heavy vehicles in 2014. The decision-making will rely on results from several key connected vehicle safety pilot studies that include the driver acceptance clinic studies and field traffic network testing. If the NHTSA passes the enforcement regulation, the detailed deployment guidelines will be provided in 2014. It will take around 5 years for the automobile industry to fully comply with the guidelines in the original equipment manufacturer and retrofit processes and for the in-vehicle device manufacturers to start providing aftermarket options. It should be noted that the NHTSA’s decisions affect only V2V applications (which require all vehicles to be equipped with DSRC devices); V2I applications are not affected by the NHTSA’s decision since they do not require 100% penetration [5].

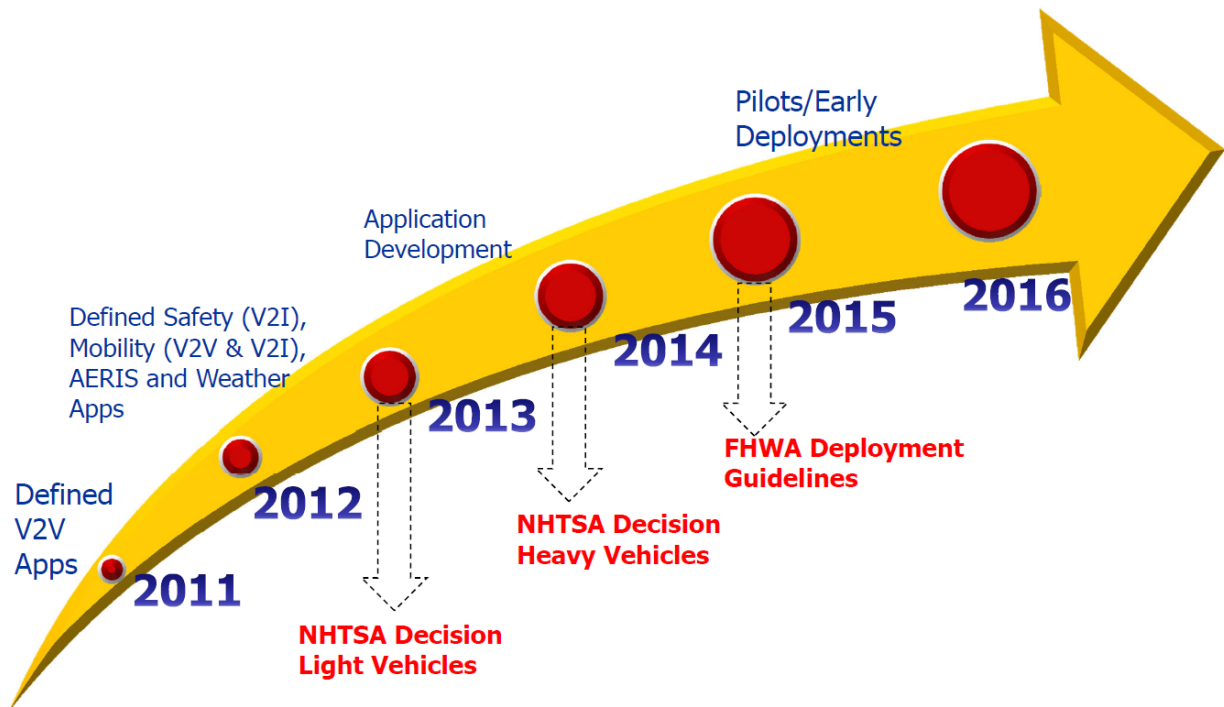


Figure 2. Milestones of the CV-DSRC Technologies [5]

4. State of the Research

The ongoing research efforts on CV-DSRC technologies include several research areas such as technologies, applications, policy, and institutional issues. The technology research focuses on the establishment of an expandable, open, and reliable platform suitable for the complexity and range of human behaviors that will interact with and impact upon the system. The applications research demonstrates the functionalities of the CV-DSRC technologies from different application areas. The CV policy and institutional issues may limit the successful deployment. Current CV-DSRC has advanced notably in the safety pilot studies that will provide data and supporting evidence for the NHTSA's enforcement decisions.

The vision for the connected vehicle safety pilot programs is to demonstrate the transformative nature and benefits of CV-DSRC technologies in terms of safety, although these benefits extendable for non-safety applications. Several highlights of the program include the following.

- **V2V/V2I safety pilots:** The safety pilot research, also called the model development studies, deploys CV-DSRC technologies in real-world road network with 2000–3000 vehicles with DSRC devices in Ann Arbor, Michigan. Volunteer vehicles equipped with V2V devices will send and receive safety warning messages 10 times per second to provide foundations for cooperative, crash avoidance safety applications [6].
- **Driver Safety Clinics:** The driver clinics study evaluates driver response to the CV-DSRC technologies within a controlled environment. The studies are currently conducted at six different locations, including Michigan, Minnesota, Florida,

Virginia, Texas, and California, with at least 100 volunteer drivers and 24 DSRC-equipped cars at each clinic [1].

- **Affiliated Testbeds:** CV testbeds are currently established at six states in Michigan, California, Florida, Minnesota, New York, and Virginia for testing the applications, services, system components, management processes, and backend services of CV-DSRC technologies. Table 2 summarizes their main characteristics and highlights.

Table 2. USDOT Connected Vehicle Testbeds [7]

Testbed	Location	Purpose	Assets	Applications
California	Palo Alto	Assess/evaluate real-world implementations, Inform future investment decisions on system management programs	Vehicles, OBEs, RSEs, backend servers	Multi-modal intelligent signal, CV mobility applications, CV safety warning
Florida	Orlando	Support 18th ITS World Congress Technology Showcase demos in Orlando	Vehicles, RSEs, servers, data management systems	SunGuide Software CV Module
Michigan	Oakland County	Research and testing resource for private developers to test DSRC-enabled applications	OBEs, RSEs, SPaT, vehicles, trailers, 3000 volunteer vehicles	Connected intersection, security network, safety pilot
Minnesota	Multiple locations	Minnesota Road Fee Test, road weather information system, testing DSRC standards	500 volunteer vehicles, DSRC safety Android apps, MnDOT snow plows	Road fee test, safety clinic, road weather information
New York	Long Island	To support the 2008 ITS World Congress in Manhattan and demonstrate capabilities of CV technologies	Vehicles, OBEs, RSEs, freeway and arterial	OBE management, DSRC wireless safety inspection, DSRC safety warning
Virginia	McLean	Test CV technologies in congested urban areas to focus on enhancing the state of the art of transportation operations research	Vehicles, OBEs (DSRC), OBEs (Cellular), RSEs, fiber network, backend servers, data warehouse	CV-DSRC, CV-cellular mobility and safety applications, multi-modal solutions

OBE: onboard equipment, RSE: roadside equipment, SPaT: signal phase and timing

The results of these efforts so far have laid solid foundation and provided valuable information for RITA and the NHTSA, enhancing decision-making and planning efforts for the future.

5. Deployment Issues and Concerns

The game-changing nature of the CV-DSRC technologies also introduces issues and concerns that may impact development and deployment.

Privacy: The CV-DSRC technologies take into account privacy issues when designing the basic safety messages to be used in V2V and V2I applications. The safety message itself is anonymous, without personal information. Minimal personal information may be necessary for the security network that manages the registration, validation, and revocation of DSRC certifications.

Data Ownership: If the NHTSA decides to proceed with DSRC, the safety messages will be generated and shared from DSRC-equipped vehicles without consent by the drivers. The data ownership can become an issue when such data is obtained and used to generate commercial IT products.

Security: The security issues of CV-DSRC technologies include the cyber security and security network. The cyber security issues refer to potential cyber-attacks on the CV-DSRC system. CV-DSRC systems are vulnerable to hackers, who could falsify vehicle safety messages or disable the communication or the device itself, which may lead catastrophic results. The security network issue is related to the registering, validating, invalidating, and roaming of the DSRC certificate. A critical step is to ensure that all DSRC devices on the road are working properly and that the vehicle safety messages being broadcasted by each DSRC device are trustworthy. A DSRC network can be as large as a cellular network, but a cellular network has stronger security and identity management systems and technologies. Thus, managing the DSRC security network can become a substantial obstacle in the large-scale deployment or enforcement of the DSRC technologies.

Driver distraction: Aside from the added safety and mobility benefits, the CV-DSRC applications do interact with drivers, potentially distracting them from operating their vehicles. This creates potential safety concerns, similar to the safety issues involved in making phone calls and sending text messages. The NHTSA developed and issued distraction guidelines for vehicle and device manufacturers and other related application or service providers [8].

Liability: The liability issues in CV-DSRC technologies occur when DSRC device failures lead to accidents. The CV-DSRC system involves both the security network and RSE, managed by the public sector, and the in-vehicle devices manufactured by the private sector. The situation can become even more complicated in the case of V2V DSRC device failures with devices of both vehicles coming from different manufacturers. The liability issues need to be addressed effectively through legislation.

Spectrum: In 1999, the FCC allocated the 5.9 GHz band for ITS applications [9]. With the rapid development in wireless communication technologies and market, especially the increasing congested Wi-Fi and cellular mobile networks, the FCC is reconsidering opening up the 5.9 GHz band (5.850–5.925 GHz) for unlicensed users [3]. This step may potentially compromise the reliability of DSRC to deliver safety and mobility applications such as collision avoidance and tolling. With the interference from other unlicensed uses, DSRC communications could be temporarily unavailable due to channel congestion and miss the window for delivering crucial safety messages, such as a collision warning, resulting in serious consequences. The transportation community lead by ITS America has responded to the related FCC Notice of Proposed Rulemaking. The FCC completed an evaluation report in January 2013 regarding this issue [9]. The concerns from the transportation community have been recognized and the discussion is still ongoing.

6. Strategic Implications for Texas

Despite the promising potential for active traffic safety applications using CV-DSRC technologies, two main uncertainties remain in the future for this technology: the NHTSA legislative decisions on DSRC enforcement, and the spectrum-sharing decision by the FCC. The former will determine if DSRC is feasible since the technology will be feasible only when most vehicles on the road have built-in DSRC devices [9]. The latter ensures that the designated 5.9GHz spectrum cannot be infiltrated by unlicensed devices, maintaining its reliability during life-and-death situations [3]. According to the agenda of both organizations, the fourth quarter of 2013 presents crucial time points when both organizations make decisions regarding these issues. It is important for Texas to observe the development in those legislative agendas and in the meantime prepare for the possible outcomes of those decisions. Meanwhile, V2I applications do not depend on the NHTSA's decisions and preparation for infrastructure connectivity—especially the data retrieval and dissemination—can be initiated. Furthermore, to achieve connectivity among vehicles, DSRC is not the sole and only option. Many proposed DSRC-based safety and mobility applications can also be implemented through the CV-cellular technologies introduced in the next chapter.

CV Technologies based on Global Cellular Wireless Communication Technologies and Telematics

1. Introduction

In parallel with the USDOT's effort on CV-DSRC technologies, the automobile industry and the research community have also explored other CV technologies for many years based on the telematics technologies and the recent development in cellular communication technologies, especially the 4G Long Term Evolution (LTE). We hereafter refer these technologies as the CV-cellular technologies. Most importantly, those technologies have already passed the initial research and development phase and are in the phase of field implementation. Another advantage of CV-cellular technologies is that they are developed by automobile, wireless communication, and IT companies that have rich knowledge and experience in the development of communication systems.

2. Technology and Applications

Vehicle Telematics

Vehicle telematics is a set of technologies that integrates the telecommunication and information technologies for safety and mobility applications of moving vehicles. Key technologies in telematics include the GPS, computing, and a large set of communication technologies applicable on moving objects. The applications of telematics have also been widely developed and many of them have been tightly integrated with daily traveler information and traffic management services. Vehicle telematics have also been considered part of the Internet of Things (IOT) [10] development, offering the Internet of Vehicles (IOV), which represents a significant mobile subnet of the IOT.

Mobile Data

The use of wireless data communications using radio waves to send and receive real-time data to and from and between devices is used by field-based personnel. Typical applications include the establishment of vehicle-based mobile data terminals for field operations and the Automatic Vehicle Location application used in transit vehicle tracking and management. Such mobile data services are usually provided by cellular providers to allow cost-effective ways of transmitting telematics information and wide field coverage of cellular network.

Vehicular Ad Hoc Network (VANET)

VANET is a technology that uses moving vehicles as nodes to create a mobile communication network [11]. VANET turns every participating vehicle into a wireless router or access point, allowing cars within approximately 100 to 300 meters of each other to connect and, in turn, create a network with a wide range. The key characteristic of VANET is the hopping or multi-hopping process when vehicles connected to different local communication areas can transfer information through "hopping" multiple intermediate vehicles. DSRC is one technology that can implement VANET. However, VANET can also be implemented by using other wireless technologies such as cellular, satellite, and WiMAX, which all can provide low-latency connectivity in moving objects. The Institute of Electrical and Electronics Engineers (IEEE) is

also actively involved in the standardization of VANET with the IEEE 802.11e standard for VANET support messages, Wi-Fi IEEE 802.11p, WAVE IEEE 1609, and WiMAX IEEE 802.16 [3]. VANET is also an intensively researched area in both computer science and transportation engineering with tens of thousands of publications in academic journals and proceedings.

Intelligent Vehicle Technologies

Integration of intelligent vehicle technologies provides a simple yet effective alternative to the CV-DSRC technologies. An embedded cellular modem, or a 3G/4G mobile device tethered to the telematics unit via Wi-Fi, Bluetooth, or other close-range personal communication technologies, can provide the needed connectivity. This forms a connectivity that can be realized with today's on-the-shelf wireless communication technologies. The technologies commonly apply to car safety systems, responding to emergency warnings generated from in-vehicle and roadside sensors. The first conceptual intelligent vehicle model was demonstrated in 2009 by Toyota [12]. An LTE-connected 2010 Toyota Prius was manufactured as part of the NG Connected project, a collaboration of automotive telematics technologies designed to exploit the applications of in-car 4G wireless connectivity.

4G LTE Connectivity

In an effort to identify complementary or alternative technologies to the DSRC technologies, the USDOT investigated the opportunities and challenges of 4G LTE on the future of CV technologies. 4G LTE is the latest generation of wireless communication with much faster transmission speed; it offers high mobility access even with objects moving at 500 km/h. Furthermore, 4G LTE is also fully compatible with the early generation technologies while offering connectivity extendibility with Wi-Fi or even wired communication systems such as cable networks. Although the expanding 4G network is facing an explosion of mobile data subscribers in the future, and the demand of using DSRC as a supplementary communication method is increasing (resulting in the spectrum complications discussed in the previous chapter), 4G still provides substantial opportunities for the CV environment. Two major trends are identified by USDOT regarding its future impact on CV environment.

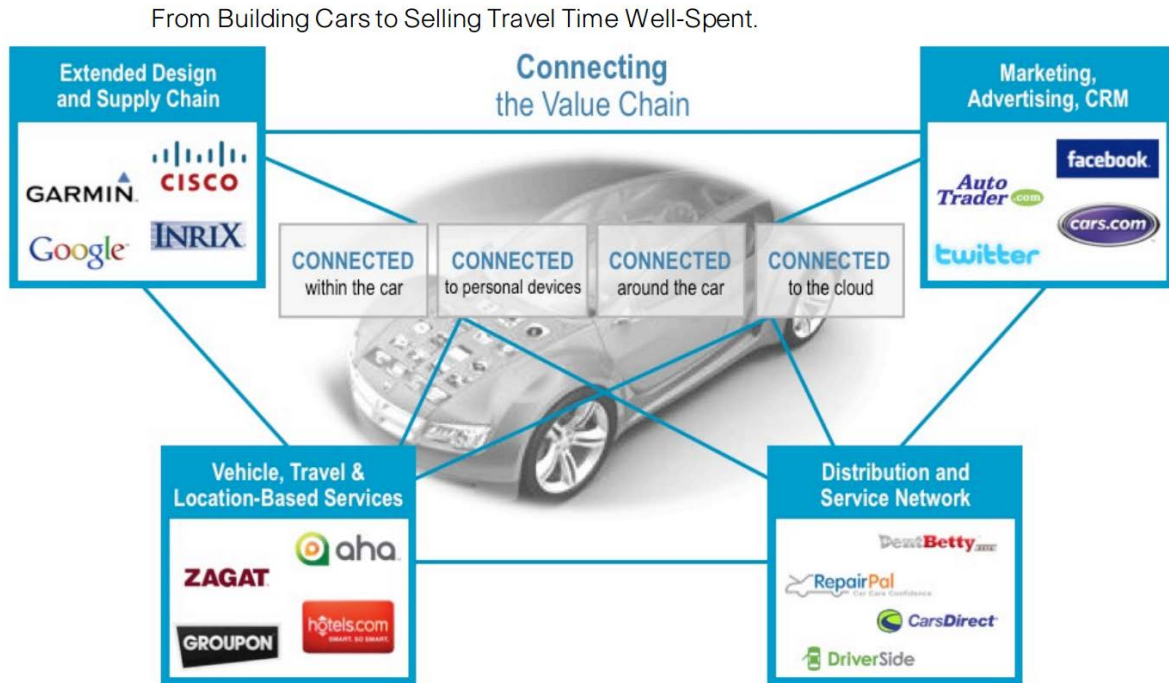
Vehicle as a Wireless Device Gateway

One industry trend in telematics is the changing role of telematics technologies itself, from the traditional embedded vertical solutions to a flatter technology platform that facilitates other technologies and application services—a gateway of sorts. This has become the key trend of the latest development of CV-cellular technologies. With the backend connectivity in place, either through cellular devices or vehicle connectivity, the development of the corresponding safety and mobility applications has become the main focus. The gateway itself should serve as an application and data hub that connects those applications with in-vehicle or received vehicle data. In the meantime, the gateway should be designed to ensure the safety of drivers through approaches such as restricting driver distractions while still allowing critical emergency warnings to be delivered in time [2].

Integration of Onboard and Cloud Data through Vehicle Gateways

In today's vehicles, data can be generated “onboard” from between 40–50 sensors and 30 electronic control units [2]. Through CV-cellular technologies, off-board data can be obtained

through cloud services facilitated by the cellular connectivity. The incorporation of cloud data can provide cost-effective alternatives to the V2I CV-DSRC technologies when transportation infrastructure data is open and provided to the cloud by transportation agencies. A rich set of cooperative CV technologies can then be applied (Figure 3). One typical example is the OnStar system available to latest Ford vehicle models and aftermarket OnStar devices [13].



Source: Cisco IBSG, 2011

Figure 3. Illustration of the Connectivity in an Intelligent Vehicle [14]

3. State of Practice

Table 3 summarizes existing efforts by leading automobile manufacturers to provide cellular connectivity to vehicles. The leading manufacturers include General Motors (GM), Ford, BMW, Audi, Nissan, and Volvo. Most of them team with communication companies such as cellular carriers and satellite radio providers. The communication technologies are usually based on 4G LTE available in the US and the Sirius Satellite radio technologies. Most of these major initiatives have been proposed since 2010.

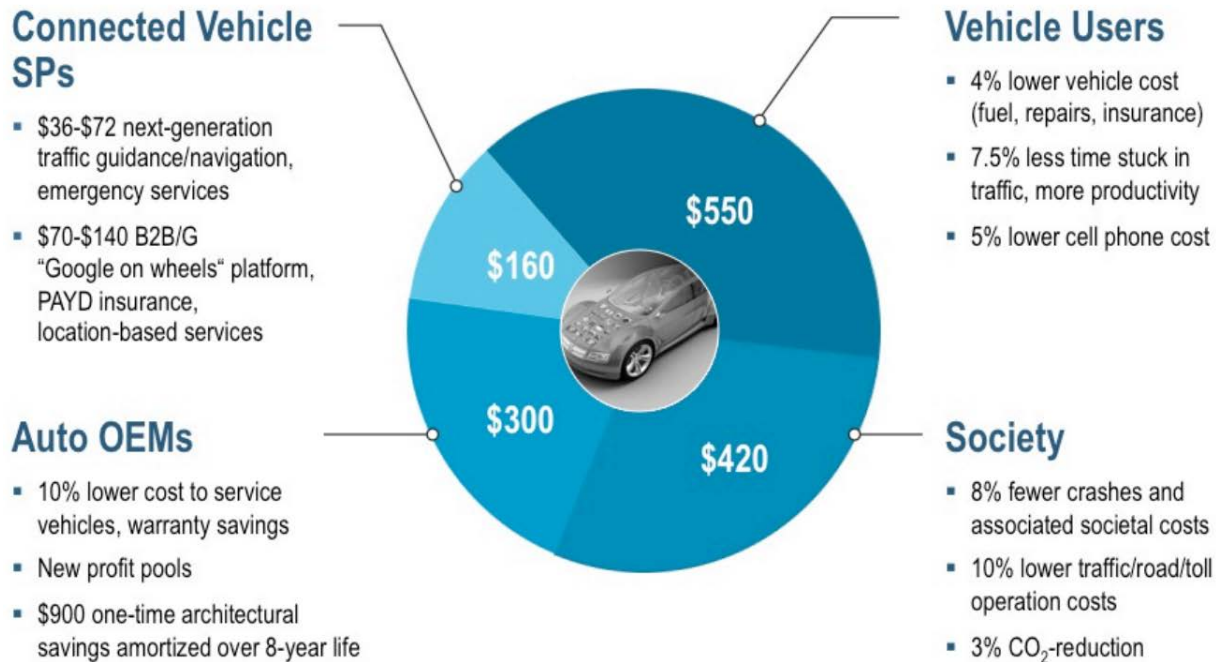
Table 3. Existing Industry Efforts on CV-Cellular Technologies

Year	Vehicle Year Model	Automaker	Communication Company	Comm. Technology	Location	Citation
2010	2010	Nissan (Leaf only)	AT&T, SiriusXM	GSM	worldwide	[15, 16]
2012	2013 (Ram and Viper)	Chrysler	Sprint		USA	[17, 18]
2012		Volvo	Ericsson			[19]
2013		Honda	AT&T, SiriusXM			[20]
2013		Hyundai	AT&T, SiriusXM	navigation HERE		[20]
2013	unknown	Nissan (Future vehicles)	AT&T, SiriusXM		US	[15]
2013	2014	Ford	SiriusXM	satellite	US	[21–23]
2013	2014	BMW	AT&T, SiriusXM	navigation HERE, 3G	US (certain models only)	[15, 23, 24]
	Currently	Audi	T-mobile	3G	USA	[25, 26]
2013	2014 (Europe), 2015 (US)	Audi	(unannounced for US vehicles)	4G LTE	US and Europe	[27]
2013	2015	GM (Chevrolet, Cadillac, Buick, GMC)	AT&T, OnStar	4G LTE chip	worldwide, (AT&T in US only)	[15, 28]

4. Deployment Opportunities and Challenges

In contrast to CV-DSRC technologies, the CV-cellular technologies are already in place. For example, with the existing cellular devices with data plans, the Bluetooth interface to the vehicles, and a safety or mobility application on the smartphone, we can easily built simple yet effective safety and mobility applications. CV-cellular technologies do not require active involvement or support from government agencies to thrive and move forward. They are mature technologies that have been actively researched and developed by the automobile industry in collaboration with wireless providers. The driving force behind such development is the market potential represented by the benefits of CV technologies (Figure 4).

Vehicle Connectivity Will Create a \$1,400 Benefit Pool per Vehicle per Year.



Source: Cisco IBSG Automotive and Research & Economics practices, 2011

Figure 4. Marketing Potential of Connected Vehicle Technologies. [14]

The deployment of CV-cellular is not without issues and obstacles. Some issues such as privacy, security, and data ownership are less severe than they are for CV-DSRC technologies; other issues, such as driver distraction and marketing, are more difficult to address than with CV-DSRC.

Privacy: The CV-cellular technologies do not have the privacy protection built into the original design like with CV-DSRC. The common privacy and security concerns regarding cellphones all apply to CV-cellular enabled vehicles. The privacy protection in CV-cellular is addressed by user agreements on sharing their personal data typically signed during the installation of the mobile applications.

Data Ownership: This is a critical issue in CV-DSRC since users generate the data but are not the clear owner of the data. In CV-cellular, the users are provided with options to determine the use of the data.

Security: Security issues in a CV-cellular system are similar to the security issues in a cellular network. The existing cyber security infrastructures and solutions in cellular network can all be used to ensure the security of the CV-cellular systems and applications.

Driver distraction: The CV-cellular technologies create more concerns about driver distractions than does CV-DSRC due to the direct integration of the technology with cellular devices and communications. The potential of having multiple devices and applications interact

simultaneously with the CV safety and mobility application can cause driver overload and lead to serious safety concerns.

Liability: The liability issues in CV-cellular are similar to that of CV-DSRC. There are more potential liable parties involved with the additional CV application providers and cellular providers. However, due to the “opt-in” process, the liability issue, at least for the responsible parties, can be clearly defined or waived.

Marketing and Sustainability: This is a special issue for CV-cellular applications. In CV-DSRC, if the NHTSA chooses to proceed with DSRC enforcement, all vehicles will be required to have DSRC devices on board. For CV-cellular applications, it is the responsibility of the application developer to promote those applications and increase market penetration. Marketing strategies need to be considered, especially when there are competitive products available for consumers to choose from. This also creates issues for the application developer. They need to consider that full penetration of the traffic flow might not be reached as well as the lack of a sustainable model that can lead to the growth of the user base and the improvement of services and functionalities.

5. Strategic Implications for Texas

The literature review indicates that the CV-cellular technologies being pursued by the automobile and communications industries are ahead of the USDOT-led CV-DSRC technologies in terms of technology maturity, and are available now. However, CV-DSRC technologies still have the advantage in active traffic safety applications with the expected full-fleet penetration of all vehicles if the NHTSA decides to require DSCR in US vehicles. The role of TxDOT in the development and deployment of CV-cellular technologies is significantly different from its role in CV-DSRC development. The development of CV-cellular applications relies on transportation agencies to provide infrastructure data (e.g., signal timing, speed limit, curvatures), traffic events such as incidents and construction, and necessary oversight and inspections to ensure the quality of those applications.

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**THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH**

0-6803-P2 Volume 3

**EMERGING TRANSPORTATION TECHNOLOGIES
WHITEPAPER: CLOUD COMPUTING AND
CROWDSOURCING**

Peter J. Jin
Dan Fagnant
Andrea Hall
C. Michael Walton

TxDOT Project 0-6803: Technology Task Force

AUGUST 2013

Performing Organization: Center for Transportation Research The University of Texas at Austin 1616 Guadalupe, Suite 4.202 Austin, Texas 78701	Sponsoring Organization: Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080
Performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.	

Background

One key issue in Texas transportation is addressing the ever-growing Texas economy, population, and the resulting travel demand with only limited budget and government resources. Efficient and cost-effective solutions for maintaining, managing, and improving the Texas transportation system have been the main target of transportation agencies in Texas for many years. Recently, the development of information, computational, and network technologies has made such solutions possible for transportation. In particular, the cloud computing and crowdsourcing technologies that have emerged in recent years provide new alternatives that can significantly improve the efficiency of data collection, archival, analysis, and dissemination in transportation. Cloud computing technology is a centralized data center solution that can replace the existing standalone data centers that have limited computational power. The technology is based on the mega-computing resources available at IT giants such as Amazon, Google, and Microsoft. The crowdsourcing technologies, facilitated by the latest social networking technologies, provide new ways of obtaining transportation data. Through crowdsourcing, users can actively participate in traffic data generation and consumption without direct interference from transportation agencies. Both technologies show great potential for improving the efficiency, transparency, and cost-effectiveness of the operations of transportation agencies in Texas.

Cloud Computing

1. Introduction

Cloud computing uses powerful data centers and IT infrastructure to efficiently deliver services and applications to end users. This technology allows businesses, such as traveler information providers, to focus on their own applications and client interfaces without significant investment in the storage and computing infrastructures. A current leading cloud computing service provider is Amazon's Elastic Compute Cloud (Amazon EC2) [1]. Researchers from the University of California-Berkeley have explored the feasibility of disseminating traveler information through cloud computing. The concept of cloud computing is also mentioned in the development of connected vehicle technologies [2] and in the context of connected cities and transportation "Big Data."

2. Applications

IBM Perspectives

The IBM approach to cloud computing primarily focuses on the IBM Smarter City solutions [3]. The solutions include services accessible over the Internet to help streamline and integrate the daily services of cities while adding visibility to their operations. The solution is based on the IBM Intelligent Operations Center on IBM SmartCloud [4]. The main service areas for smarter city operations identified by IBM are summarized in Figure 1.

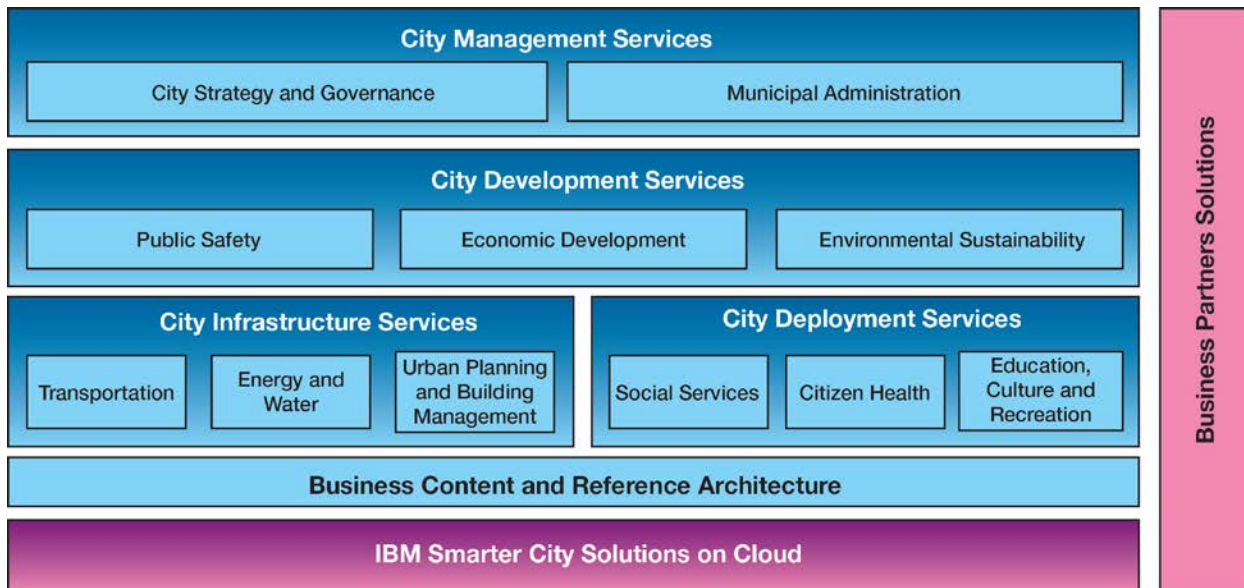


Figure 1. IBM Smarter City Solution Service Areas [5]

IBM believes, based on their experiences with IBM’s own IT organization and customers, that the migration to cloud computing has already realized significant savings, reducing IT labor by up to 50% and IT support costs by up to 40% [5]. Additional financial benefits include the lower upfront capital costs when compared to a traditional IT deployment. Figure 2 illustrates the potential cost savings a city may achieve through cloud computing.

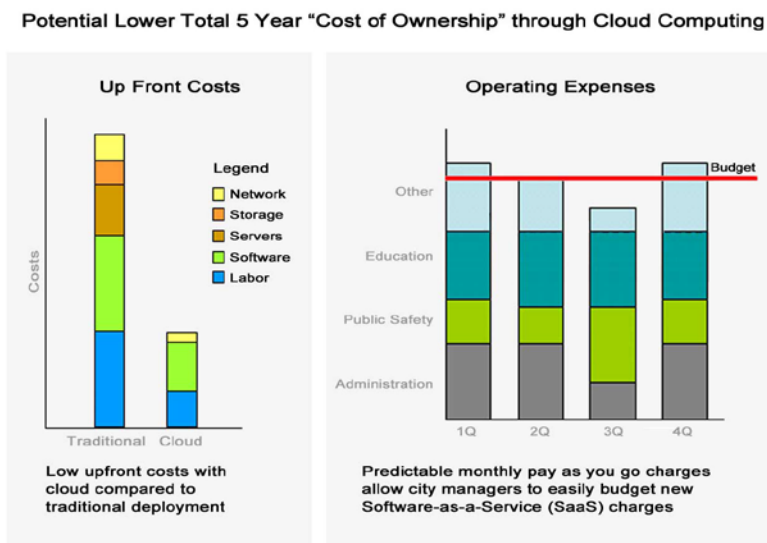


Figure 2. IBM Projection on Cost Savings through Cloud Computing [5]

Without the need to establish and maintain IT infrastructures, significant upfront cost savings can be achieved. Furthermore, since cities focus on the applications and usage of cloud data, city leaders can match their cloud service levels with their long-term growth objectives and budget plans.

Cisco Perspectives [6]

Cisco's perspectives on cloud computing services differ from IBM's. Cisco identified three major driving factors in IT organization innovations: the user demands, evolving technologies, and changing business/service landscapes (Figure 3).

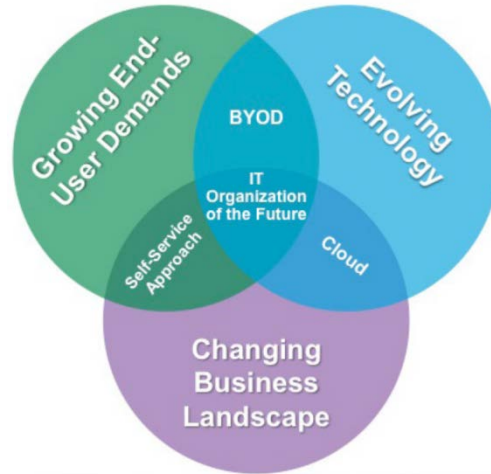


Figure 3. Cisco Cloud Perspectives [7]

The cloud is one solution that leverages the three interacting elements, along with self-service applications and BYOD (Bring Your Own Device) [8] applications. Cisco envisions distributed cloud data centers and services rather than the centralized super-cloud centers proposed by IBM. Cisco provides services to establish private clouds rather than hosting the data services for the clients. This strategy of implementing cloud services allows the clients to keep their data and services confidential and protected behind their own firewalls, which is suitable for government agencies with sensitive information and data.

Big Data Perspective

“Big Data” refers to the integration and analysis of high volume (amount of data), high velocity (speed of data in and out), and high variety data (data types and sources) that cannot be easily handled by relational databases. Strictly speaking, transportation data still have not reached the true “Big Data” era yet. However, with the development of connected vehicle technologies and traffic sensing technologies, the transportation data start to exhibit more and more characteristics of “Big Data,” especially when data collected from multiple data sources needs to be integrated. Cloud computing is an efficient tool for handling Big Data. Furthermore, cloud computing can effectively integrate the transportation data collection, processing, analysis, and dissemination for use in traveler information, transportation management, and planning applications.

3. The State of Cloud Computing Services

The basic cloud computing infrastructures include the cloud services, cloud platform, cloud storage, and cloud infrastructures. The prevailing cloud computing providers are based on different fundamental service models: infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS). IaaS is the most basic and hardware-oriented service

usually provided by IT companies with heavy investments in cloud computing resources; SaaS is mostly user-oriented and software services [9, 10]. The PaaS model, in between IaaS and PaaS, is more developer-oriented. Meanwhile, in 2012, NaaS (network as a service) and CaaS (communication as a service) were also introduced, representing models of a telecommunication-centric cloud ecosystem related to the connected vehicle environment [11]. Representative IaaS providers include Amazon EC2, Google Compute Engine, HP Cloud, Rackspace, etc. Amazon EC2 has been dominating the cloud computing market for many years and is still the largest and most reliable service open to the general public. Representative PaaS providers Engine Yard, Google App Engine, and Windows Azure Cloud usually deliver computing platforms or environments for developers to develop and run their cloud-based software applications. SaaS providers focus on software-centric services, providing on-demand software for end users such as Google Apps [12], Microsoft Office 365 [13], Host Analytics [14], etc. Figure 4 illustrates the different service layers and providers in cloud computing.

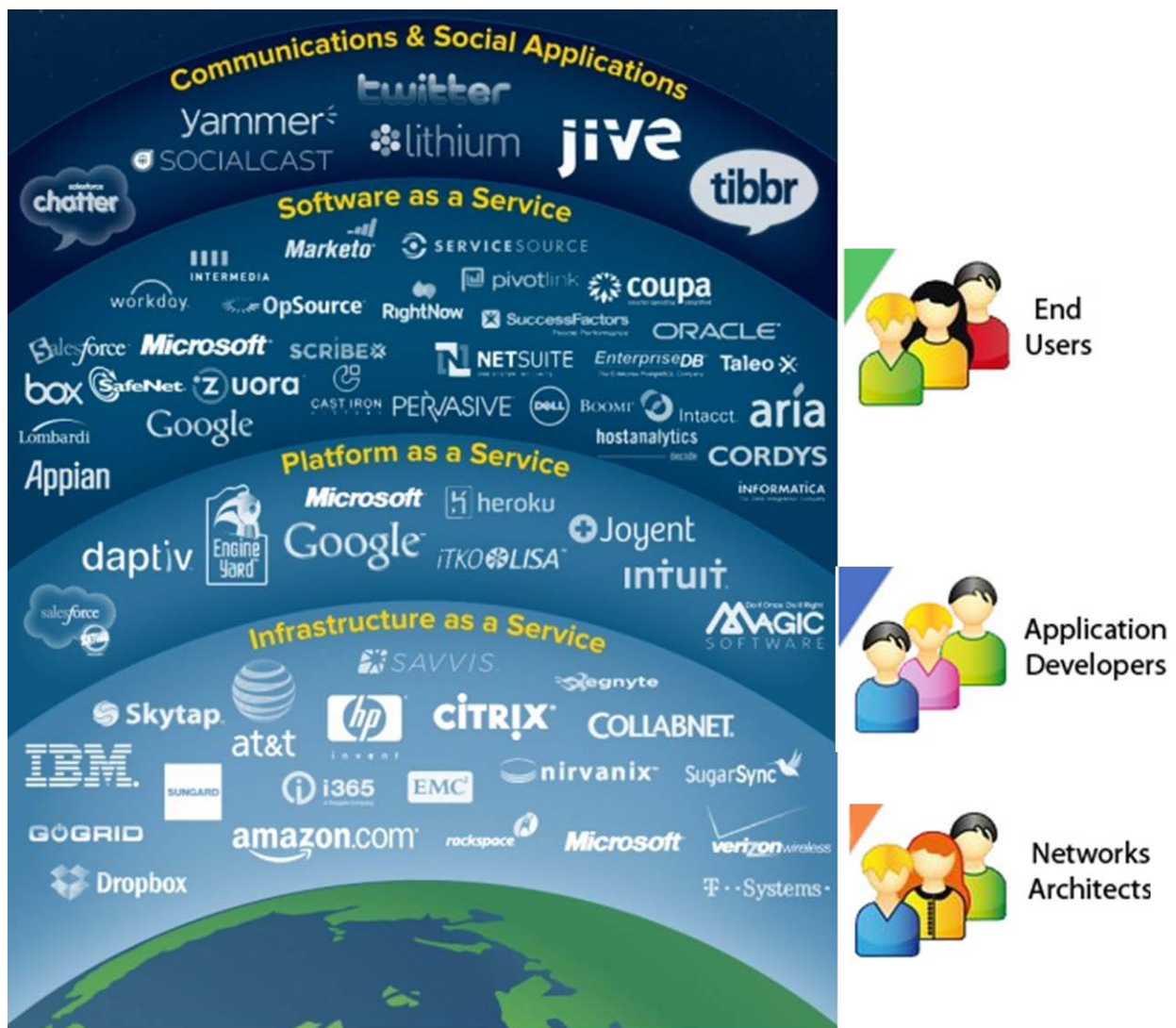


Figure 4. The Cloud Computing Stratosphere [15]

4. Deployment Issues and Challenges

In recent years, cloud computing has been frequently mentioned in both public and private sectors as a means to improve the efficiency and cost-effectiveness of their services and operations. However, the deployment of cloud computing is not without issues and challenges.

Privacy: The privacy issue of cloud computing has been cause for debate for many years. Depending on the operations of the cloud services and cloud service providers (CSP), the privacy issues differ. For the public cloud envisioned by IBM, clients migrate their IT infrastructure to a centralized cloud to achieve significant savings in on hardware and IT labor. However, their data and communication then become vulnerable to unwanted backend monitoring and access, as the recent reveal of the secret NSA (National Security Agency) program indicates. For the private cloud promoted by Cisco, clients can maintain the data and communication privacy within their companies or agencies at the cost of losing some computation power of the super data centers in public cloud. With either cloud setup, employees may be concerned that, by committing to a cloud structure, their own personal data and communications are under constant surveillance, which may also raise concerns.

Security: The security issue of cloud computing is two-fold. On one hand, with all the data and information stored in a single cloud computing center or service, the outcome of potential cyber-attacks could be severe without the distributed storage and physical firewall protection offered by traditional IT infrastructure. On the other hand, by moving data into super cloud data centers operated by Amazon or IBM, users can benefit from the more comprehensive and state-of-the-art cyber protection, data recovery, and redundancy solutions that may not be easy or cost-effective to deploy at the client side.

Data Ownership: The data ownership issue of cloud computing is not discussed enough. In cloud computing, the original data providers, the clients, are considered in “possession” of the data; while the CSPs are considered the “custodian” of the data. Such split data ownership roles cause complications in data management and legal issues, especially for sensitive data [16]. The CSP custodian role allows them to back up client data for data recovery or redundancy services, as well as delete data or disable services in the case of service contract issues.

Data Migration: The migration to the cloud is not as easy as it sounds. For transportation agencies with a lot of analog data (not yet digitized) or based upon legacy systems, migrating their data system may not be feasible with limited funding or human resources. Therefore, it is critical to identify core and central businesses that are needed in the cloud to accelerate the migration process while provide interfaces and IT infrastructures for accessing un-migrated data.

Authorization: For government agencies such as TxDOT, the security assessment, authorization, and continuous monitoring for the cloud products and services are quite crucial to ensure the safety and security of public assets. The US General Services Administration provides the Federal Risk and Authorization Management Program (FedRAMP) [17] to assist government agencies that seek similar services. Many CSPs have participated and been cleared in this program, including Amazon, HP, Lockheed, etc. [18].

5. Implementation Strategies

Cloud computing offers significant savings and benefits for future operations in transportation agencies in Texas. With a sophisticated industry in place since last decade, implementation faces no major technological bottlenecks. The main considerations for implementation include the following.

- Understanding of agency needs: Understanding the agency needs will help transportation agencies select the appropriate cloud service types and levels.
- Development of cloud-based transportation applications and solutions: Aside from the basic data access and the out-of-the-box cloud applications, it is critical for transportation agencies to customize and develop their own applications based on the agency needs and the needs from the general public.
- Sustainability of the services: With the system partly controlled and managed by third parties in some cloud solutions, it is important for government agencies to consider the sustainability of the continuing the services, considering future demand increase and budget fluctuations.
- Data protection and management: This is the most critical challenge facing all cloud computing services. For transportation agencies, it is critical to prepare with necessary procedures, policies, and legislations to ensure the data stored in the cloud are properly managed, accessed, and distributed.

In summary, cloud computing technologies provide new opportunities for Texas transportation agencies to improve their efficiency and reduce operating costs to achieve the goal of “best in class.” At the same time, transportation agencies will need to conduct comprehensive reviews and planning to understand the benefits and risks and develop cost-effective migration strategies.

Crowdsourcing

1. Introduction

The emergence of the crowdsourcing concept coincides with the rapid development of cloud computing services in late 2000s [19]. It is a practice of obtaining services, ideas, and content from volunteers, part-time participants, and the general public rather than a specific group under contract, as in outsourcing, or the traditional employees or suppliers. The basic principle behind crowdsourcing is that by canvassing a large crowd of people for ideas, knowledge, skills, or participation, the quality of content generated will be superior.

Facilitated by the rapid development in computing technologies, communication technologies, and social media technologies, crowdsourcing practice has significantly increased in popularity. For transportation agencies that deal with a system that serves and is funded by the general public, crowdsourcing offers new opportunities to improve public education, public involvement, and public relations in daily operations and planning efforts.

2. State of the Practice

Web-based Crowdsourcing

Prevailing crowdsourcing practices can be classified into several major categories as crowd voting, wisdom of the crowd, crowdfunding, microwork, and inducement prize contests [20].

- Crowd voting: This practice uses an online platform, e.g., website or mobile application, to gather the opinions and judgment of a target group on a certain topic.
- Wisdom of the crowd: This is an effective way of collecting a large amount of information and collective knowledge. The representative examples include Wikipedia and the numerous Question-Answer platforms operated by Yahoo and Microsoft.
- Micro/macrowork: This crowdsourcing platform host either divides a large task into small-scale tasks or gathers small tasks from different projects; participants can select and help complete the tasks that interest them. The most representative platform is Amazon's Mechanical Turk platform [21].
- Inducement prize contests: This Web-based idea competition usually involves providing incentives such as cash prizes to participants for contributing their ideas and innovations. The most well-known contests include the Netflix Prize project, which sought algorithms improving their site's recommendation engine [22].

Figure 5 illustrates the current web-based landscape of crowdsourcing [23]. Many well-known IT companies have practiced crowdsourcing activities, such as Netflix, Cisco, Amazon, and Yahoo. Existing knowledge and web inquiry platforms such as Wikipedia and Yahoo Answers are also seen as crowdsourcing practices.

major events such as incidents, constructions, weather, disasters, or simply cultural and sports events that may affect transportation.













- **User experience optimization:** A user opt-in option can automatically collect user statistics and crash reports for improving and upgrading a mobile application. Best practiced by Google and Apple with their mobile operation systems, the technology helps improve the user experiences and identify bugs and design defects in their operating system (OS).
- **Leveraging mass reach:** Mobile crowdsourcing can also provide effective tools to connect government agencies with the general public interactively and in real time.
- **Product testing:** Companies have used mobile crowdsourcing for testing the functionality, performance, and reliability of their developed applications. This presents new opportunities for future traffic safety and mobility applications developers.



Figure 6. Mobile Crowdsourcing Architecture [24]

Aside from Waze, many other potential mobile crowdsourcing applications are related to transportation. Those applications can serve as effective data collection and dissemination platforms. Table 1 summarizes the most popular transportation-related applications focusing on their transportation features, OS, user data collection, ratings, and privacy control level. Common transportation features include location sharing, transit information, social media, transit information, traffic report, GIS maps, and navigation. The Data Collection column summarizes the key transportation data types, clearly indicating whether the data is actively (A) submitted by users or passively (P) collected after they agree to a data sharing agreement. The ratings were gathered from the Social Networking section of Apple’s iTunes Store as of July 2013 [25]. Based on the main functionality of those applications, there are three main types of applications, social media, transit information, and navigation applications. This list only contains applications with an average rating higher than 3 (on a scale of 1 to 5) and more than 1,000 reviews.

Table 1. Major Transportation Related Smartphone Applications [25]

Application	Transportation Features	Operating System	Data Collection	Ratings (# reviews)
 Facebook	Location sharing	All mobile OS, Web	Location info (A)	4 (264,5075)
 Twitter	Location sharing	All mobile OS, Web	Location info (P) Special events (A)	3.5 (233,733)
 Foursquare	Location sharing	All mobile OS, Web	Location info (A) Special events (A)	4 (83,870)
 Yelp	Location sharing	All mobile OS, Web	Location info (A)	3.5 (178,726)
 Embark (12 cities)**	Transit information	iOS	Transit events (A) OD data (A)	4.5 (1641) NYC
 WAZE*	On-road social media, location sharing, traffic report, GIS map, navigation	iOS, Android, Web	Location info (A/P) OD data (P/A) Trajectories (P/A) Traffic events (A)	4.5 (124,485)
 MapQuest Maps	Social media, location sharing, traffic report, GIS map, navigation	iOS, Android, Windows, Web	Location Info (A/P) Trajectories (P) OD data (A) Traffic events (A)	3 (77,642)
 Glympse	Trajectory sharing, GIS map, traffic report, navigation	iOS, Android, Windows phone, BlackBerry OS, Web	Location info (A) Trajectories (A/P) OD data (A)	4 (3,722)
 MotionX GPS	Trajectory/location sharing, GIS map, navigation	iOS	Location info (A) Trajectories (A) OD data (A)	3.5 (14425)
 Inrix	GIS map, navigation, arrival time, sharing	All mobile OS, Web	Location info (P) Trajectories (P) OD data (A)	3 (25,946)
 Trapster	Trajectory/location sharing, GIS map, navigation, traffic report	All mobile OS, Web	Location info (A/P) Trajectory (A/P) OD data (A) Traffic events (A)	4 (1,561)
 HopStop**	Traffic info, GIS map, navigation, traffic report	iOS, Android, Web	OD data (A), Traffic events (A)	3 (9,590)

*Recently purchased by Google Inc. **Recently purchased by Apple Inc.

3. Implementation Strategies for Texas

A proper strategy is important for Texas transportation agencies to benefit from crowdsourcing technology. The major considerations include the following.

Platform Plan and Development

Similar to cloud computing, the technology itself has been practiced by many IT companies and many successful examples can be found, such as Amazon's Mechanical Turk, Wikipedia, and Waze. Most of them position themselves as a service platform or marketplace, rather than as active content publishers or application developers. This is an important success factor as it gives users a sense of ownership and incentivizes them to contribute information, content, or volume to the service. The key issue for the deployment in transportation agencies is how to plan and develop platforms that meet agency needs while also providing platforms that are open and easy to use, thus maximizing the benefits for both the agencies and the general public.

Incentives and Feedback for Participants

Most successful crowdsourcing practices so far involve the participants with incentive models, providing case prizes, intellectual gain, or information. In transportation applications, such incentives can be traveler information regarding traffic conditions, incidents, construction, or road weather to ease travel, or financial incentives for valuable information related to incidents and crashes. However, the key is to maintain a sustainable incentive model that allows participants to benefit while not causing financial issues for the operation and maintenance of the crowdsourcing services.

Service Maintenance and Security

Transportation agencies can either be actively involved in maintaining and operating the crowdsourcing services as part of the traffic management center duties or leave it to private businesses, taking advantage of their existing IT and customer service resources. Either way, there are maintenance and security issues. Agency operation means staff and IT resources must be devoted to crowdsourcing services and the responsibility of securing and protecting the service is also the responsibility of agencies. Since crowdsourcing services are usually open to the general public, the internal defense, e.g., internal firewalls cannot be relied on and comprehensive cyber defense strategies need to be applied. If a private-sector organization is running the service using their own resources, the agencies still need to oversee their operations to ensure the quality and security of the service.

Quality Control and Public Relations

The keys to the success of many existing crowdsourcing services lie in the content diversity and content quality. At the same time, crowdsourcing potentially allows inclusion of false information from unreliable or biased sources. When deploying crowdsourcing applications, the agencies should develop the necessary procedures and strategies to address those scenarios.

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