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16. Abstract

Advances in vehicle automation and communication can dramatically reduce the economic and comprehensive costs of U.S. crashes. This report quantifies in detail the crash-related gains of various vehicle automation and connectivity features and anticipates their near-term and long-range impacts on car crashes in Texas. It also documents the best practices for the Texas Department of Transportation (TxDOT) and other agencies to most cost-effectively facilitate Texans' adoption and use of top technologies. This study estimated the adoption of connected and autonomous vehicle (CAV) technologies over the long term through the use of two surveys. The study also reviewed CAVs' impacts on safety, and estimated crash count and crash cost reductions via various CAV technologies. Finally, the report presents a benefit-cost (B-C) analysis that identifies top design and system management strategies for departments of transportation to follow, in the transition to new technologies and travel choices. This work provides practical recommendations emphasizing safety to assist TxDOT in optimally planning for these new technologies using a holistic and qualitative approach.

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CENTER FOR TRANSPORTATION RESEARCH

Implications of Connected and Automated Vehicles on the Safety and Operations of Roadway Networks: A Final Report

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Related TxDOT Projects

This report benefits from work conducted in TxDOT Project 0-6838, which addressed another facet of this rich and developing field. For details and associated project publications for that and other TxDOT research initiatives, please see the CTR-hosted TxDOT library catalog at http://ctr.utexas.edu/library/.

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List of Acronyms

AADT .... annual average daily traffic
AASHTO .... American Association of State Highway and Transportation Officials
ACC .... adaptive cruise control
AEB....................... automatic emergency braking
ASC....................... alternative specific constant
ATMS .... Advanced Traffic Management Software
AV......................... automated or autonomous vehicle
B-C........................ benefit-cost
BCI........................ backup collision intervention
BCR....................... benefit-cost ratio
BSM .... blind spot monitor
BSW...................... blind spot warning
CACC.................... cooperative adaptive cruise control
CAV .... connected and autonomous vehicle
CDS....................... Crashworthiness data system
CICAS................... cooperative intersection collision avoidance system
CLW...................... control loss warning
CSW...................... curve speed warning
CV .... connected vehicle
DeltaS.................... maximum speed differential
DeltaV................... vehicle velocity change
DNPW................... do not pass warning
DOT .... department of transportation
DR .... deceleration rate
DRS....................... dynamic ridesharing
DSRC .... dedicated short-range communication
EDM...................... External driver model
EM......................... Event management
ESC .... electronic stability control
ESS........................ environmental sensor station
FCW...................... forward collision warning
FHWA................... Federal Highway Administration
GES .... General estimates system
GMD .... global misbehavior detection
GPS .... global positioning system
HOV...................... high-occupancy-vehicle
HV......................... human-operated vehicle
IMA....................... intersection movement assist
IP........................... internet protocol
IR........................... interval regression
ITS......................... Intelligent Transportation Systems
LCW...................... lane change warning
LDW .... lane departure warning
LKA .... lane-keeping assistance

LTA....................... left-turn assist
LTAP/OD............. Left turn across path of opposite direction
MAIS..................... Maximum abbreviated injury scale
MaxD .... maximum deceleration rate
MaxS..................... maximum speed
MNT...................... Maintenance Division
MUTCD .... Manual on Uniform Traffic Control Devices
NASS .... National Automotive Sampling System
NHTSA .... National Highway Traffic Safety Administration
OBE....................... onboard equipment
OP .... ordered probit
PATH .... Partners for Advanced Transportation Technology
PDO....................... property-damage only
PET .... post-encroachment time
PHEV .... plug-in hybrid electric vehicles
PKI .... public key infrastructure
PTN .... Public Transportation Division
RDCW................... road departure crash warning
RFID .... radio-frequency identification
RLVW................... red light violation warning
RSE .... roadside equipment
SAV....................... shared autonomous vehicle
SCMS.................... Security Credentials Management System
SSAM.................... Surrogate Safety Assessment Model
SSGA .... stop sign gap assist
SSVW .... stop sign violation warning
TJA........................ traffic jam assist
TMC...................... traffic management center
TPP........................ Transportation Planning and Programming I
TRB....................... Transportation Research Board
TRF .... Traffic Operations Division
TSR .... traffic sign recognition
TTC .... time to collision
VMT...................... vehicle-miles traveled
V2I .... vehicle-to-infrastructure
V2Ped.................... vehicle-to-pedalcyclist
V2P .... vehicle-to-pedestrian
V2V....................... vehicle-to-vehicle
V2X....................... vehicle-to-anything

Chapter 1. Executive Summary

1.1 Introduction

Smart driving technologies have drawn significant attention in recent years, due to their rapid development and potential safety, mobility, and environmental benefits. Autonomous vehicles (AVs), connected vehicles (CVs), and connected-autonomous vehicles (CAVs) are the most significant technological advances in personal transport the world has seen in over a century, with a promising future of safer and more convenient transportation. Self-driving vehicles may dramatically reduce the 90% of all crashes that result from driver error (NHTSA 2008), while reducing driving burden and allowing for more productive or restful travel.

The emergence of new automotive technologies will shift the dynamic between car and driver over the coming decades. New technologies can eliminate a large number of crashes, through effective crash avoidance systems. Vehicle control systems can also smooth traffic flows, through automatic control of acceleration and brakes, so that the driving experience and fuel consumption can be simultaneously improved. When vehicular automation and connectivity are fully interactive and adoption rates are high, use of new traffic signal control systems will become possible, which can reduce intersection and freeway delay significantly and increase safety of operations.

CAVs are destined to change how the Texas transportation system operates. TxDOT is responsible for the nation's most extensive state-level network, so it is imperative that TxDOT explore CAVs' potential impacts on the design, maintenance, and operation of the state's transportation systems. Research into CAVs' mobility, environmental, legal, and safety implications for the state of Texas was conducted by UT Austin's Center for Transportation Research (CTR) under Project 0-6847. This Executive Summary highlights key results of that work, including practical safety-focused recommendations to assist TxDOT in optimally planning for these new technologies.

Success of smart driving technologies will depend on various public and private stakeholders' efforts, and a thorough understanding of CAVs' impacts requires a multi-disciplinary approach. This report seeks to clarify the scope of smart driving technologies for DOT staff, and help them understand the state of the practice associated with CAV research, development, and deployment. This work anticipates the evolution of the light-duty vehicle fleet and its use under various market scenarios (involving federal regulations, changing technology pricing and consumer willingness to pay over time); and it provide recommendations for DOTs to implement over the short, medium, and long terms. This report identifies potential best practices for TxDOT and other agencies to most cost-effectively facilitate Texans' adoption and use of top safety and mobility technologies.

Presently, the legal landscape of CVs and AVs is one of much uncertainty and flexibility. Current Texas laws do not directly address such technologies; if this ambiguity remains unaddressed, it could hamper the state's ability to best prepare for CAV use. The National Highway Traffic Safety Administration (NHTSA) advocates adoption of laws that enable researchers to test CAV technologies while ensuring the safety of test subjects and roadway system users. Most observers, including NHTSA, agree that CAV research still needs development before driverless vehicles are ready for use by the public. In addition to setting the stage for advanced testing, the State must address questions concerning liability in the event of a crash involving CAV technologies like electronic stability control and lane-keeping assistance. Existing crash litigation for conventional vehicles should be updated to reflect the increasing use of automation technologies. Based on police-reported crashes in 2013, the total comprehensive crash costs involving light-duty vehicles is near $645 billion a year across the U.S. The potential safety benefits of using CAV technologies nationwide is estimated here to offer hundreds of billions of dollars in annual comprehensive crash savings.

Implementation of CAV technologies can amplify the safety benefits, in terms of economic costs from goods, services, and productivity lost as well as comprehensive costs reflecting social issues, such as pain, suffering, and quality of life loss. Results suggest that eleven CAV technologies, such as Automatic Emergency Braking and Cooperative Intersection Collision Avoidance Systems, may save Americans over $100 billion each year in economic costs and roughly $400 billion per year in comprehensive costs. These estimates draw data from the most recent U.S. crash database and are based on pre-crash scenarios of the critical event leading to a collision and the avoidance or reduction in severity of crashes with each technology. Based on the analysis, complete automation has the greatest potential to mitigate crashes. While penetration of complete automation may be a long-term goal, automatic emergency braking (AEB) and cooperative intersection collision avoidance systems (CICAS) are two highly beneficial technologies that can be implemented more widely at a faster rate than full automation.

Assessing the potential adoption rate of CAVs by the public is another crucial aspect of implementation. A national survey and a Texas survey assessed the current state of public opinions towards existing and forthcoming CAV technologies. The U.S.-wide survey's fleet evolution results indicated that around 98% of the U.S. vehicle fleet is likely to have electronic stability control and connectivity by 2030. Long-term fleet evolution suggests that Level 4 AVs are likely to represent 25% to 87% of the U.S. light-duty vehicle fleet in 2045. Results suggest that 41% of Texans are not ready or willing to use shared autonomous vehicles (SAV) and only 7% hope to rely entirely on an SAV fleet, even at $1 per mile. AVs and SAVs are less likely to affect Texans' decisions about moving closer to or farther from the city center: about 81% indicated a desire to stay at their current location.

The report identifies three categories of implementation strategies for TxDOT. It provides recommendations for TxDOT to pursue in the short term (next 5 years), medium term (five to fifteen years), and long term (15+ years) to facilitate and prepare for CAV prevalence, as described below.

1.2 Recommendations

Since much CAV-related technology is still in the development or testing phase, it is important that research and testing efforts be sustained. In the near term, we recommend that a department-wide TxDOT working group be established to continue the research and testing needed to assess the technically feasible and economically reasonable steps for TxDOT. This working group should also create and periodically update an annual policy statement for CAVs, and a separate plan for non-CAV vehicle support and operations during the transition to CAVs. Another short-term recommendation includes the Traffic Operations Division working in conjunction with other divisions and districts to oversee research and testing to additional or modified traffic control devices and signage that will enhance CAV operation. Finally, we recommend that the Transportation Planning and Programming Division develop and continuously maintain a "working plan" for facilitating early adaptors of CAV technology, in particular the freight and public transportation industries.

For the medium term, we recommend that the department-wide working group continue developing CAV policy statements and plans. The group should also coordinate CAV issues with

AASHTO, other states, Transportation Research Board committees, the Texas Department of Motor Vehicles, and the Texas Department of Public Safety. Additionally, the group should provide to the Legislature technical advice as well as recommendations for legislative policy making and changes or additions to the Texas Transportation Code and Texas Administrative Code. In the medium term, the Traffic Operations Division, in coordination with other divisions, the districts, and other stakeholders, should expand the research and testing from off-road test facilities to actual intersections, in addition to initiating research and testing for CAV-appropriate lane management operations—beginning with "platooning" and "CAV Only" lanes. Finally, the Transportation Planning and Programming Division should research, test, and recommend incentives (for example, micro-tolling, time of day operations restrictions, etc.) for the control of congestion as well as increased vehicle-miles traveled induced by CAVs.

It is important that the lessons learned from experience be implemented to further evolve the transportation policies and modify the regulations for them to stay relevant. As a part of its long-term strategy, the TMO and TPP should continue steps needed to identify the optimal traffic demand management strategies that are economically feasible and environmentally compliant. TMO should also coordinate efforts with the engineering design divisions division (the Design Division and the Bridge Division) and the Maintenance Division to test and ultimately adopt changes to the Department's manuals optimized for CAV/SAV operations.

The engineering design divisions should undertake a similar approach to adopt roadway design elements that allow high speed, but safe, CAV roadway operations in rural and uncongested suburban areas.

1.3 Report Structure

This report is divided into five chapters. Chapter 1 is an executive summary that highlights the major findings and recommendations of this project. Chapter 2 systematically synthesizes existing and emerging smart driving technologies (CAV technologies) to conduct safety, system operation, and benefit-cost (B-C) analysis. Chapter 3 outlines project surveys that were undertaken at the U.S. and Texas level to gain insight into the public's perceptions of technologies, determine their willingness to pay for CAV technologies, and develop matrices of market penetration rates for various CAV technologies over time, under different regulatory, pricing, and consumer willingness-to-pay scenarios. Chapter 4 analyzes the safety benefits of CAVs. Chapter 5 conducts a B-C analysis on the various CAV technologies. Chapter 6 provides the major findings and recommendations of this research project. In addition, a project guidebook (0-6849-P1) was also developed to accompany this research report. It is a summation of the recommendations, analysis, and findings, and was developed to assist a TxDOT or local jurisdiction transportation planner as they navigate the continued development and rollout of CAVs.

Chapter 2. Identifying CAV Technologies

To understand the potential impacts of smart driving technologies, the project synthesized existing and emerging smart driving technologies to (i) gain an initial understanding of their impacts on safety, operations, and design, and (ii) align these with TxDOT's strategic goals, for developing final project recommendations. A hybrid approach combining a multi-round literature scan with expert interviews was undertaken. An initial qualitative analysis was conducted to pinpoint noteworthy impacts of these technologies. The scope was limited specifically to smart driving technologies that are likely to have significant public sector involvement. The research team completed these tasks:

- Conducted an initial scan of media to define an extensive list of smart driving technologies and their categorization, in alignment with the National Highway Traffic Safety Administration (NHTSA)'s taxonomy.
- Scanned media reports, technical reports and presentations, manufacturers' websites, and academic papers to determine the current state-of-practice of each technology.
- Conducted expert interviews.
- Developed initial analysis to describe each technology's likely impacts on safety, operations, and design.

2.1 Identifying Smart Driving Technologies

To clarify the scope of smart driving technologies and understand their impacts, an extensive literature review was conducted, relating to the definition, functions, working mechanisms, maturity, limitations, and cost of each technology. NHTSA's four-level taxonomy of autonomous vehicles (AVs) was adopted to facilitate the discussion (the research team also compared this with the Society of Automotive Engineers categorizations).

2.1.1 NHTSA's Taxonomy

NHTSA has defined five vehicle automation technology levels in all (with Level 0 indicating full driver control). Levels 0 through 2 encompass technology that is commercially available today; Levels 3 and 4 are currently being tested.

- Level 0, or no automation, means that the driver is completely responsible for the primary vehicle controls: braking, steering, throttle, and motive power.
- Level 1, or function-specific automation, indicates that one or more specific control functions are automated. Examples include electronic stability control (ESC) and pre-charged brakes (where the vehicle automatically assists with braking to enable the driver to regain control after skidding or to stop faster than possible by acting alone). Other examples include adaptive cruise control (ACC) and lane-keeping assistance (LKA).
- Level 2, or combined-function automation, implies automation of at least two primary control functions designed to work together to relieve the driver's control of those functions. Examples include a combination of ACC and LKA.
- Level 3, or limited self-driving automation, indicates that vehicles at this level enable the driver to cede full control of all safety-critical functions under certain traffic and

environmental conditions. This technology allows the driver to rely heavily on the vehicle to monitor for changes in those conditions, which may require the driver to interfere from time to time. The driver is still expected to be available for occasional control, but after a warning and some comfortable transition time (3 to 5 seconds).

- Level 4, or full self-driving automation, indicates that the vehicle is designed to perform all driving functions for the entire trip. This design anticipates that the driver will provide the destination or navigation input, but the driver is not expected to be available for vehicle control at any time during the trip.

Recognizing the prominent safety, environmental and mobility potential of emerging automotive technologies, NHTSA released a document entitled "Preliminary Statement of Policy Concerning Automated Vehicles" (NHTSA, 2013). In this document, NHTSA provides definitions of different levels of automation, current automated research programs at NHTSA, and principles recommended to states for driverless vehicle operations (including but not limited to testing and licensing). According to NHTSA definitions, the term *automated vehicles* refers specifically to "those at which at least some aspects of a safety-critical control function (e.g., steering, throttle, or braking)" occur without direct driver input. Vehicles that can provide safety warnings, but cannot control functions, are not fully automated.

According to these definitions, with increasing levels of automation, drivers have decreasing engagement in traffic and roadway monitoring and vehicle control. From level 0 to level 4, the allocation of vehicle control function between the driver and the vehicle falls along a spectrum from full driver control, driver control assisted/augmented by systems, shared authority with a short transition time, shared authority with a sufficient transition time, to full automated control. Table 2.1 provides an outline of the five automation levels based on the NHTSA definitions.

Several mainstream companies, such as Google, Toyota, Nissan, and Audi, are developing and testing their own prototypes (Smiechowski 2014). With rapid advances in vehicle automation and connectivity, NHTSA (NHTSA 2013 & 2014) recognizes key policy needs for connected and autonomous vehicles (CAVs). Navigant Research (2014) estimated that 75% of all light-duty vehicles around the globe (almost 100 million annually) will be autonomous-capable by 2035. In accordance with this timeline, Litman (2014) expects that AVs' beneficial impacts on safety and congestion are likely to appear between 2040 and 2060. If AVs prove to be very beneficial, Litman (2014) suggests that human driving may be restricted after 2060. Thus, there is a chance that AVs may become prevalent in the near term. If Texans are not prepared for such a shift, it could prove very costly for their travel. For example, Level 3 vehicles may require excessive buffers (for 8-second handoffs to their drivers), potentially increasing congestion.

Section 2.2 provides further detail on the driving technologies.

Table 2.1: Five automation levels based on NHTSA (2013) definitions

	Vehicle Controls	Traffic and Environment (Roadway) Monitoring	Examples
L0	Drivers are ***solely responsible*** for all vehicle controls (braking, steering, throttle, and motive power)	Drivers are solely responsible; system may provide driver support/convenience features through ***warnings***.	Forward collision warning; lane departure warning; blind spot monitoring; automated wipers, headlights, turn signals, and hazard lights, etc.
L1	Drivers have overall control. Systems can ***assist or augment*** the driver in operating one of the primary vehicle controls.	Drivers are solely responsible for monitoring the roadway and safe operation.	ACC; automatic braking (dynamic brake support and crash imminent braking); lane-keeping; ESC.
L2	Drivers have ***shared authority*** with system. Drivers can cede active primary control in certain situations and are physically disengaged from operating the vehicles.	Drivers are responsible for monitoring the roadway and safe operations and are expected to be ***available*** for control ***at all times*** and ***on short notice.***	ACC combined with lane centering.
L3	Drivers are able to ***cede full control*** of all safety-critical functions ***under certain conditions***. Drivers are expected to be available for occasional control, but with ***sufficient transition time.***	When ceding control, drivers can ***rely heavily on the system*** to monitor traffic and environment conditions requiring transition back to driver control.	Automated or self-driving car approaching a construction zone, and alerting the driver sufficiently in advance for a smooth transition to manual control.
L4	Vehicles perform ***all safety-critical driving functions*** and monitor roadway conditions for an entire trip. ***Drivers*** will provide destination or navigation input, but are ***not expected to be available for control*** at any time during the trip.	System will perform all the monitoring.	Driverless car.

2.2 Driving Technology Synthesis

2.2.1 Level 0 Technologies

Forward Collision Warning

NHTSA defines a forward collision warning (FCW) system as "one intended to passively assist the driver in avoiding or mitigating a rear-end collision via presentation of audible, visual, and/or haptic alerts, or any combination thereof." An FCW system has forward-looking vehicle detection capability, using sensing technologies such as cameras, radar, and Lidar. Sensor data are processed and analyzed, and alerts are provided if a collision with another vehicle is imminent.

Blind Spot Monitoring

There are two different types of blind spot monitors (BSM): active and passive. An active BSM generally uses radar or a camera to detect when another vehicle gets close to the BSM-equipped vehicle. If any such vehicles are detected, the BSM-equipped vehicle will notify its driver. The type of notification can depend on how likely it is that two vehicles will collide; as the likelihood of collision increases, so does the magnitude of the warning that the driver receives. The other type of BSM is the passive, which involves only additional mirrors. Car manufacturers offer the choice to have a special small convex mirror added in the corner of the regular rearview mirror, which can provide additional visual access to the blind spot.

Volvo was the first to introduce blind spot technology in 2005 under the trade mark of Blind Spot Information System (BLIS). Originally BLIS used cameras but the newest BLIS technologies use radar. Many other manufacturers currently have very similar blind spot technologies as well, e.g., Audi's Side Assist. A more advanced system is available on Infiniti's models. Infiniti's blind spot system consists of two sub-systems: in addition to the blind spot warning, there is a blind spot intervention sub-system. The former notifies the driver of vehicles in the blind spot while the latter will work to keep the vehicle in its lane if it is not safe to change lanes.

Active blind spot detection usually comes as an optional feature in most mid- to high-end cars. Purchasing this add-on will increase the vehicle price by around $250–500. There are plenty of models where a consumer can buy the entire safety package (which might also include lane departure warning, FCW, and cross traffic alert) for around $1000 (Howard, 2013).

Lane Departure Warning

Lane departure warning is similar to blind spot monitoring. The system detects the approaching vehicles' speed and distance from neighboring lanes and warns the driver of potential danger if the driver wants to change lanes. A lane departure warning system can also warn the driver if it detects that the car is leaving its current lane.

It is anticipated that in the future, the system will incorporate features such as monitoring the driver's eye activities to determine drowsiness (Carmax, 2015). Lane departure warning is available on Infiniti models as an option; the package runs from $3,600 to $10,500.

Traffic Sign Recognition

Traffic sign recognition (TSR) is a technology capable of identifying and displaying upcoming traffic signs that may be missed by drivers. A typical system functions using a camera to detect oncoming traffic signs, a recognition system that identifies the meaning of the signs recorded by the camera through image processing, and a display pane. The road sign information can be displayed on either the vehicle's instrument panel cluster or on the driver's navigation system screen. TSR systems' reliability, especially at high speeds, depends on the camera's image resolution. In a natural environment, TSR may encounter three main challenges, namely poor lighting and visibility, the presence of other objects, and variation of traffic and road signs.

The first TSR systems were developed by Mobileye (a technology company that develops vision-based advanced driver assistance systems) in 2007 and have been available since 2008 on the BMW 7 Series as a dual vision and satellite navigation system. Honda also released its advanced driver assistive system called "Honda SENSING" in late 2014 (Honda Motors Co., 2014). According to Mobileye, TSR systems have been developed with high detection accuracy and may have additional information from digital maps and navigation systems (Mobileye, 2015). TSR systems can also function in conjunction with other Mobileye technologies, including lane-centering technology, intelligent headlight control, and other systems that use visual sensors.

Left-Turn Assist

Left-turn assist (LTA) systems use a camera and GPS to warn drivers against attempting a left turn into an intersection where the conditions are unsafe. When LTA is activated, laser scanners installed on the car's front begin sensing for approaching cars, trucks, and even motorcycles up to 100 meters (330 ft.) away. If the sensors detect an approaching vehicle from the opposite direction and the driver's vehicle continues to move into the intersection, the LTA system will generate both a warning and may activate the vehicle's automatic braking (which turns into Level 1 automation). The LTA is designed to work at very low speeds, less than 10 km/hour (roughly 6 mph).

LTA was first mass publicized by BMW in 2011 and further research is currently being conducted on utilizing V2V communication (NHTSA, 2014). V2V communication increases safety by using a wireless local area network to detect other vehicles with similar concealed devices. Caltrans and the University of California at Berkeley's Partners for Advanced Transportation Technology (PATH) program have performed research on intersection collision avoidance systems within the past few years (Caltrans Division of Research, Innovation and System Technology, 2013). The research tested driver attitudes and behaviors when making left turns at signalized intersections, and found that 78% of the time, drivers conformed to the LTA system's guidance.

Adaptive Headlights

Adaptive headlights can adjust the direction as well as the brightness to best fit current traffic and surrounding environment. This ensures that the driver has sufficient lighting while at the same time ensuring that the light only minimally interferes with other drivers on the road. For this reason, the adaptive headlight can greatly improve safety. A study released in 2012 by the Highway Loss Data Institute found that Acura, Mercedes, Mazda, and Volvo vehicles with swiveling headlights were involved in 5% to 10% fewer insurance claims than vehicles without them.

Adaptive headlights have already been widely used in Europe and Japan, and many manufacturers (e.g., BMW) currently have adaptive headlights technology. As of 2013, Toyota had sold 16,600 cars in Europe and Japan with this adaptive headlight technology that is currently unavailable in the United States. As the advancement of headlight technology has been steadily increasing, there has been increasing pressure on federal policymakers to change regulations (Gitlin, 2014). NHTSA stated that it would look into the issue and plans to start a research study to assess the adaptive headlights (Nelson, 2013).

The additional price of having this technology added on to one of these cars was approximately $600, a number that is expected to decrease with economies of scale (Nelson, 2013).

2.2.2 Level 1 Technologies

Adaptive Cruise Control

ACC systems allow vehicles to maintain a constant speed under operation, just as a conventional cruise control system would. However, when approaching a slower moving vehicle, drivers with a conventional cruise control system must respond by braking and slowing down to adjust their speed to the vehicle ahead. In contrast, an ACC system is able to address this concern by detecting the speed of the leading vehicle and adjusting its own speed accordingly. In ACC, the system maintains a comfortable and safe distance between itself and the leading vehicle. Once the space ahead is clear again, the ACC will accelerate the vehicle back to the desired cruising speed. Currently, most ACC systems use radar or laser (less popular) headway sensors and a digital signal processor to determine the distance and speed of the vehicle ahead (Honda Motors Co. Inc., 2015). Sensor information is transmitted to a central controller, which reads the desired settings of the driver. The central controller also controls the engine and/or braking system to respond appropriately.

ACC systems were first introduced into the consumer market in the early 2000s (TRW, 2011). Early systems deployed both lasers and radars on vehicles, but radars are more popular because they function better in inclement weather. Nevertheless, an ACC's abilities are still limited by heavy rain and snow and will shut off under severe weather conditions.

While many automobile manufacturers still do not include ACC systems as a standard feature, the technology is offered in many luxury models. ACC systems currently range in price from $500 to $2,500 (Howard, 2013). ACC systems are expected to further integrate with crash detection systems and other V2V communication technology.

Cooperative Adaptive Cruise Control

Cooperative adaptive cruise control (CACC) works by having leading vehicles send messages via V2V communication to following vehicles that give a recommended speed and (in some cases) lane assignment. After the following vehicle receives the message, the driver will usually not need to take any action because the vehicle will respond appropriately on its own. With CACC, drivers still need to supervise the vehicles closely. As such, CACC is a driver assistance function, and drivers are still fully responsible for the driving.

There are two main objectives of CACC technology, as discussed below. There is no industry-wide consensus on which of the two benefits is more important. The first objective is improving driver comfort. By allowing a CACC vehicle to adjust speeds (and possibly, though rarely, lanes) without the need for driver interference, a driver will feel much more comfortable. This will allow drivers to focus on keeping the vehicle safe (Jones, 2013). Another objective of

CACC is to greatly increase highway throughput by allowing closer headway between vehicles that are both CACC-equipped. This is possible because the brake reaction time (BRT) of a CACC vehicle following another CACC vehicle is only 0.1 seconds. This is almost five times less than the fastest human BRT, which is 0.47 seconds. In addition, throughput will increase, given that any change ahead due to braking, hazards, etc., can be immediately relayed to following vehicles, preventing abrupt slowdowns or stops (van Arem, van Driel, & Visser, 2006).

There are some limitations with CACC. Reduced time gaps between two vehicles can only occur when both vehicles have CACC technology. Therefore, the impact of CACC relies heavily on market penetration. One study found that CACC technology needs to have at least 40% market penetration to have any considerable impact (van Arem, van Driel, & Visser, 2006).

Automatic Emergency Braking

Also known as forward collision avoidance, automatic emergency braking (AEB) has the potential to significantly decrease collisions by automatically braking a vehicle when an imminent collision is foreseen. AEB systems are made up of sensors that observe and categorize objects within range, control systems to process the data produced by the sensors, and an automatic braking actuation system to physically stop or slow the vehicle.

To assess the impacts of AEB, (Doecke, Anderson, Mackenzie, & Ponte, 2012) analyzed and recorded data that included vehicle trajectories, speeds, braking location, and impact locations from 103 real-world crashes. This study showed that AEB technologies are capable of reducing the impact speed of unavoidable crashes, as well as preventing some crashes altogether. They also estimated that the baseline system was able to prevent 54% of all unobscured pedestrian crashes, 63% of all rear end crashes, and 22% of all straight crashes on fixed objects. These results strongly indicate that by application of a baseline AEB system, the number of crashes involving visible pedestrians, rear end collisions, and objects struck head on would decrease significantly. Results also showed that a reduced impact speed for unavoidable accidents would be accomplished for many other collisions.

A major complication with the current AEB design is its inability to differentiate between an actual impending collision and a false alarm. However, this issue may possibly be resolved as more advanced AEB technologies continue to emerge.

Lane Keeping

Lane-centering and lane-keeping technologies are used to keep automobiles from drifting out of a lane on high-speed roads. The system is designed to function as a safety tool rather than a fully hands-free driving mechanism. With lane-centering, the adapted system uses electronically controlled steering to maintain a center position in the lane. The technology uses a camera mounted on a vehicle's windshield to watch the lane markers on the road; the camera is able to recognize both yellow and white lines. If the camera detects that the driver is beginning to drift out of a lane without the use of a turn signal, the device will alert the diver with a warning sound, and then activate the electronic power steering control to steer the vehicle back into the center of the lane (Toyota Motor Corp., 2015). Electronic steering is a safety device that may be overridden by the driver.

There are several limitations to current lane-centering technology. The cameras use visible light and require clear lane markings in order to function. Inclement weather and reduced visibility in low-light conditions are also major concerns. In addition, many systems have a minimum speed requirement (Brandon, 2013). Costs for this technology average currently around $5000 and is offered by Honda, Buick, Nissan, Ford, and a variety of other automobile brands (The Economic Times, 2013).

Electronic Stability Control

ESC is potentially the most beneficial safety technology introduced to date. It is an extension of antilock brake technology and traction control system technology (Sivinksi, 2011). ESC is one of the main active safety systems (meaning it works to prevent accidents rather than working to prevent injuries once an accident occurs). It is designed to ensure that that a driver can always be in full control of the vehicle. It works to prevent skidding and rollovers, which can often happen during high-speed maneuvers or on slippery roads on rainy days (MEA Forensic Engineers & Scientists, 2013).

ESC works by measuring the steering input and comparing this to the yaw angle (i.e., how much the car has actually turned). If there is any difference in these values, then the ESC will automatically apply brakes on any of the wheel(s) as needed so that the car steers in the desired direction. Also, if needed, the engine throttle can be lowered to avoid power skids (Cars.com, 2012).

ESC imparts significant safety benefits. In 2011, a report to the USDOT found that the amount of all fatal car crashes was reduced by 23% for those that have ESC. Furthermore, the amount of single-vehicle fatalities in a car was reduced by 55% (Sivinksi, 2011). The study also noted that, though ESC is beneficial everywhere, it is particularly effective in locations that are prone to ice, hail, and/or slush during the winter season. However, it is important to not overlook the fact that there is always the small possibility that when an accident does occur, the presence of the ESC may have contributed to the control loss (MEA Forensic Engineers & Scientists, 2013).

Since 2012, all new passenger vehicles, trucks, or busses weighing less than 10,000 pounds are required to have ESC systems, as per Federal Motor Vehicle Safety Standards. Given that the life span of some vehicles is more than 20 years, not all vehicles on our roads will have ESC until after 2030; however, most vehicles will probably possess this technology soon after 2020.

Parental Control

Parental control aims at increasing the safety of teenage drivers. This feature is designed to reduce the risk and severity of crashes by using a series of different technologies that control teenage driving behavior.

The first parental control system introduced by Ford, MyKey (Ford, 2015), includes features such as speed control, which allows the owner to set a limit of 80 mph; volume control that allows the owner to adjust the volume of the radio remotely; a belt reminder system that can mute vehicle's radio and chime for few seconds; a fuel reminder that is issued earlier than usual; and a speed reminder set at 45, 55, or 65 mph. Chevrolet's newest model Malibu, on sale toward the end of 2015, will provide the "Teen Driver" system. This tool can "help encourage safe driving habits" (General Motors, 2015) by providing a series of features such as stability control, front and rear park assist, side blind zone assist, rear cross traffic alert, forward collision alert, daytime running lamps, forward collision braking, traffic control, and front pedestrian braking. Given the early life of this tool, at the moment there are no available data or analyses to quantify the benefits of this measure. However, presuming that this feature will be widely developed by other manufacturer competitors (in the U.S.), parental control could become within few years an affordable standard option.

2.2.3 Level 2 Technologies

Compared to the L0 and L1 systems, L2 and L3 systems place greater control and decision-making on the vehicle's automated components. This section describes major Level 2 technologies.

Traffic Jam Assist

Traffic jam assist (TJA) functions on limited access highways at slow speeds (Marinik et al., 2014). This system provides full control of driving in congested conditions. Under these two conditions, primary lateral and longitudinal controls are ceded by the driver. The driver will have direct supervision of the vehicle during this process, will receive continuous system feedback, and is still responsible for the overall operation of the vehicle. The Mercedes S-Class features a representative TJA system. The driver is expected to be engaged in driving with TJA, with hands on the steering wheel. If the system detects that the driver is not touching the steering wheel, a warning will be issued and the TJA function will be disabled after a few seconds. The European HAVEit project (Highly Automated Vehicles for Intelligent Transport)—designed to "develop technical systems and solutions that improve automotive safety and efficiency" (Strauss, 2010) — demonstrated this concept on heavy trucks.

High Speed Automation

General Motors has described a "super cruise" system, with one option providing full-speed range ACC in conjunction with lane-keeping. Cameras and radars are used for sensing, and the system can automatically steer, accelerate, and brake in highway driving. Drivers may leave hands off the steering wheel until the driver wants to change lanes or when the system can no longer handle deteriorating road conditions, or when an unexpected issue occurs. Other car manufacturers developing similar products include Honda (Europe), Infiniti, Audi, and BMW. Infiniti's system automatically reduces the discrepancies between the intended and actual path, and claims to reduce driver fatigue by reducing fine-grained steering adjustments. BMW's system not only provides lateral and longitudinal control, but also responds to merging traffic from the right and can perform a lane change when safe. Google's driverless cars) can operate up to 75 mph on highways in this mode. Google's car combines ACC and lane-keeping, but does not change lanes automatically.

Automated Assistance in Roadwork and Congestion

One system demonstrated in Europe's HAVEit project was automated assistance in roadwork and congestion. This system aims to enable automated driving through a work zone, so as to support the driver in overload situations like driving in narrow lanes (Strauss, 2010). It considers the possibility that lane lines are not accurate, and it uses other objects, such as trucks, beacons, and guide walls, for guidance.

2.2.4 Level 3 Technologies

In Level 3, direct supervision by drivers is not needed in conventional situations. When the driver is required to resume control, these technologies allow sufficient transition time. This section outlines some specific Level 3 technologies.

On-Highway Platooning

In a platoon, vehicles can have a shorter headway between each other. This technology allows a human to drive the lead vehicle, followed closely by fully AVs in platoon formation. A prototype of this technology was developed in Europe's SARTRE project (Safe Road Trains for the Environment) using Volvo cars and trucks. PATH has demonstrated this technology in California as well.

Automated Operation for Military Applications

The U.S. Army sponsored development of the Autonomous Mobility Applique System, a program designed to retrofit existing military trucks with a range of systems, from active safety to full Level 3 automation. The purpose of this project is to allow military vehicles to operate on any road types and off-road, with or without a driver in full control.

2.2.5 Level 4 Technologies

Google's Driverless Car

In May 2014, Google revealed a prototype driverless car that does not have pedals or a steering wheel. In December 2014, Google delivered a fully functioning prototype and planned to test it on San Francisco Bay Area roads beginning in 2015. According to the latest update from Google in December 2014 (Google Self-Driving Car Project, 2014), a safety driver is still needed to oversee the vehicle, and manual controls are needed in the current testing stage.

These driverless cars have not yet been tested in heavy rain or snow. Moreover, Google's driverless car primarily relies on pre-programmed route data, so it cannot recognize traffic lights. In addition, this prototype is limited in identifying trash and debris on roadway. Its Lidar technology cannot spot potholes or recognize humans signaling the car to stop. Google plans to resolve these issues by 2020.

Kill Switch

A dead man's switch, or kill switch, is a safety-oriented feature that is installed to give the "driver" the ability to cease operation of the vehicle in the case of an emergency or driver incapacitation. The dead man's switch has been most commonly used in the railway industry in the form of a lever or pedal that must be manually engaged for the machine to remain active. If disengaged, the machine then would alarm the driver, slow to a stop, and shut down. Conceptually, this type of switch is ideal for a train on tracks, but the use of such switch in a vehicle on a roadway with other vehicles is far more complicated.3.6.3 Automated Valet Parking

Auto-valet refers to technology designed to assist with or fully perform the act of parking. Over the last few years, luxury vehicles have added parking assistance options that allow the user to find a parking space and simply control the gas and brake pedals while the vehicle independently maneuvers the steering wheel until it is parked.

In 2013, Ford unveiled its "Fully Assisted Parking Aid" feature. This feature allows the driver to find a parking spot and get out of the vehicle, leaving it to park itself. The advantage of getting out of the vehicle prior to parking is that the vehicle will now be able to fit in much tighter spaces, allowing parking lots to make more efficient use of space. It also allows for safer parking (McGlaun, 2013). There was speculation that this feature would be released on some 2015 Ford models but this has not yet happened.

A more sophisticated version of the valet feature is the "Remote Valet Parking Assistant" by BMW. This feature only requires the driver to drive into the parking lot/structure and get out. The driver will then tell the vehicle to go park itself through an application on a smart device. The driver will receive notification on the device when the vehicle has parked itself. When the driver is ready to leave, he or she will tell the car to come to parking lot exit via the smart device. An added benefit of this technology, over Ford's technology, is that it will save drivers' time. BMW has stated that its technology "does not require expensive changes to the infrastructure of existing parking garages" (Kable, 2014).

An initial screening of existing technologies was refined based on their significance through internal team discussion. A total of 20 smart driving technologies were identified (Table 2.2), along with each item's automation level, and the team's appraisal of its technological maturity, safety benefits, and potential need for TxDOT involvement.

Table 2.2: List of CAV technologies: benefits, maturity, and TxDOT involvement

Technology	Automation Level	Maturity Time Frame	Major Safety Benefits	Safety Benefit Significance	Maturity	TxDOT Involvement
Forward collision warning	Level 0: No Automation	Short	Prevent rear-end collision	High	High	Infrastructure
Blind spot monitoring		Short	Reduce crash risk at merging and weaving areas	High	High	Policy
Lane departure warning		Short	Prevent lane departure crashes	High	Medium	Infrastructure
Traffic sign recognition		Short	Assist driving	Intermediate	Medium	Infrastructure
Left-turn assist		Short	Prevent potential conflict	High	Medium	Policy
Pedestrian collision warning		Short	Prevent pedestrian collision	High	Medium	Policy
Rear cross traffic alert		Short	Prevent backing collision	High	Medium	Policy
Adaptive headlights		Short	Improve light condition and visibility of environment	Intermediate	High	Policy
Adaptive cruise control	Level 1: Function Specific Automation	Short	Prevent rear-end collision	High	High	Policy
Cooperative adaptive cruise control		Short	Prevent rear-end collision	High	Medium	Policy
Automatic emergency braking		Short	Prevent rear-end collision	High	Medium	Policy
Lane keeping		Short	Prevent lane departure crashes	High	Medium	Infrastructure
Electronic stability control		Short	Prevent rollover	High	High	Policy
Parental control		Short	Prevent speeding	Intermediate	Medium	Policy

Technology	**Automation Level**	**Maturity Time Frame**	**Major Safety Benefits**	**Safety Benefit Significance**	**Maturity**	**TxDOT Involvement**
Traffic jam assist	Level 2: Combined Function Automation	Medium	Driving assist	Low	Medium	Policy
High speed automation		Medium	Driving assist	High	Medium	Policy
Automated assistance in roadwork and congestion		Medium	Driving assist	High	Medium	Policy
On-highway platooning	Level 3: Semi-Automation	Long	Driving assist, prevent rear-end crashes	Intermediate	Medium	Policy
Automated operation for military applications		Long	Prevent human fatalities	Unknown	Low	Policy
Self-driving vehicle	Level 4: Full Automation	Long	Replace human drivers	High	Low	Both
Emergency stopping assistant		Long	Response when human drivers lose control	High	Low	Policy
Automated valet parking		Long	Convenience feature	Low	Low	Both

2.3 Expert Interviews and Surveys

To gain a deeper understanding of the smart driving technologies and provide a basis for later quantitative analysis, a set of survey questions were developed and instrumented online (these can be found in Appendix A and B). Through the survey, the team aimed to characterize smart driving technologies' current status, recommendations on top technologies, performance metrics, and potential risks and barriers associated with the large-scale deployment. The survey questions cover the current status, recommendations, performance metrics, and potential risks and barriers for smart driving technologies. The team also reached out to internal experts from the University of Texas, Southwest Research Institute, and the University of Utah, who work in areas of intelligent transportation, traffic management, and automotive technologies.

2.3.1 Top Recommended Technologies

The team asked the respondents to provide the top five smart driving technologies that they think will bring the most benefits in the next 10 years; Table 2.3 lists those technologies.

Table 2.3: Top five CAV technologies over next 10 years

1. Level 4 automation (including auto-pilot and shared AVs)
2. Intersection collision avoidance (including left-turn assist), especially as part of an evolving cooperative intersection collision avoidance system
3. Advanced driver assistance systems, such as blind spot warning, lane departure warning and lane keeping, FCW, and AEB.
4. Adaptive cruise control
5. Dynamic route guidance and data sharing

Specific barriers to implementation of the technologies varied by the technology cluster. Cybersecurity, reliability, and infrastructure preparedness were seen as most significant for dedicated short-range communications (DSRC)-based vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technology, with liability being an additional concern for the former. Price and infrastructure preparedness were most significant for cellular communication. For Level 2 automation, liability and price were seen as the greatest barriers. Level 3 automation shares these barriers, alongside cybersecurity. Relative to Level 3 automation, our surveys showed that public acceptance replaced liability as a top barrier for Level 4 automation.

Most respondents found safety features of Level 0 and Level 1 technologies to be the most promising for Texas transportation over the next 10 years. There is a strong belief towards the value of Level 4 (driverless) cars. Across all categories, cyber-security is the most frequently mentioned barrier to implementation. Price is the factor hindering higher level automation, and infrastructure needs are more significant for connected vehicles (CVs) rather than for AVs. Besides these factors, liability is another concern. Public acceptance was regarded a major concern regarding adoption of Level 4 automation, and is not so serious for other technology types.

2.4 Potential Impacts

2.4.1 Benefits and Risks to Drivers

Smart driving technologies can change the driving paradigm in the long run. With the L3 and L4 technologies, the vehicles themselves will play the major role in fulfilling all tasks for driving, and human drivers will cede authority of control over the vehicles. Compared to human drivers, smart driving technologies offer the following additional benefits. These benefits can address the human errors caused by limited vision, fatigue, over- and under-reaction and fall into three major categories:

1. Situational awareness: Smart driving vehicles are able to see all around simultaneously, and have the ability to communicate quickly with other smart vehicles and devices on the road or roadside.
2. Shorter reaction times: Smart driving vehicles can potentially greatly reduce reaction times and correspondingly relax headway requirements. In general, smart driving vehicles' reaction times and computer precision may also permit reduced safety margins, in the forms of narrowed lanes and higher speed limits in work and school zones.
3. Fatigue and distraction-free driving: Smart driving vehicles eliminate fatigue, distraction, and drinking as crash causes.

While smart driving technologies offer the above benefits to drivers and may in turn bring fundamental changes to the safety, mobility, and environment of transportation systems. Some risks are also envisioned with the new system.

- **Cyber-security:** Smart driving vehicles are subject to cyber-physical threats, due to the heavy usage of wireless communication, navigation, and computing components.
- **Reliability:** In extreme conditions, such as bad weather, the sensing capability of automated cars can become worse, the same as a human driver. Also automotive software systems may have bugs and cannot respond to certain special situations. These factors altogether can undermine the system reliability.
- **Complications of human-machine interactions:** In Level 2 and 3 automations, the shared authority between human drivers and automation components can pose challenges in complicated driving scenarios, when the ability to switch between the two is a necessity. Seamlessly transitioning the authority between automated components and human drivers in response to developing situations will require a comprehensive and intuitive interface.
- **Liability:** When human drivers and automation components have shared authority over driving, the liability issue requires more careful legislative considerations.

2.4.2 Impacts on Safety

Ninety percent of crashes are due to human factors. Smart driving technologies can offset many such errors (Table 2.2 lists technologies and crash types that they can address). It is worth mentioning that risk compensation is often an issue to consider when systems are improved (e.g., soon after cruise control was introduced, the crash rate increased as that convenience allows drivers to pay less attention to the road). Safety from vehicle automation and V2V communications may affect a number of behaviors, including the mode and route decisions for vehicle occupants and more vulnerable users. For example, greater safety may encourage bicyclists and pedestrians to take riskier (but faster) routes through or along major arterials and intersections, or result in more jaywalking. Trust in automation may similarly encourage drivers to pay less attention to the road. Increased risk may offset the benefits of automation on the safety of the traffic network. To better appreciate such impacts, trip, mode, and route choice models should be modified to include the effects on safety behaviors, including risk compensation.

2.4.3 Impacts on Infrastructure

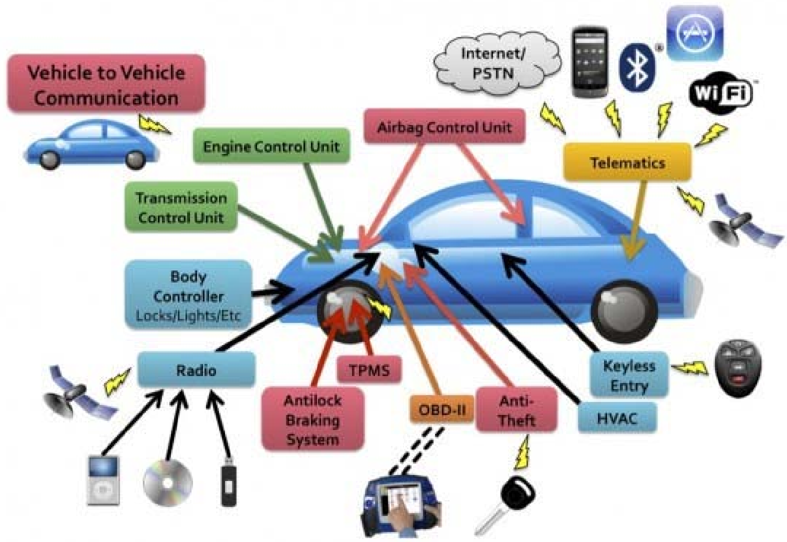
The transportation system consists of road infrastructure (pavement, traffic signs, marking) and cyber infrastructure (detectors, signal controllers, communication systems). Smart driving technologies will influence both aspects.

Road Infrastructure

Smart driving technologies will influence transportation infrastructure in terms of design and operations. The current infrastructure is designed primarily for human drivers. Due to the safety benefits, dramatic crash reductions may precipitate a significant reduction in, or elimination of, infrastructure and activity that currently supports, or is a result of, vehicle collision events. This includes a wide range of current economic domains, such as emergency responders (police, EMTs, firefighters, medical helicopters), hospital and emergency room capacity, overall healthcare costs, insurance costs, a lower demand for new cars, and fewer collision repair services. On the other hand, since smart driving vehicles rely on sensors (e.g., cameras) to recognize the surrounding environment, the requirements for lane markings, traffic signs, and roadside devices will have to increase to ensure safety for road users.

Cyber Infrastructure

Smart driving technologies allow collection of more real-time data through vehicular onboard sensors, and from these data, traffic and road conditions can be inferred. This can change current schemes of detector-based data collection and management. Probe data will be acquired and processed through so-called vehicular cloud architectures (Figure 2.1 illustrates this scenario).



Source: www.gps4us.com, accessed 04/30/2015

Figure 2.1: Illustration of vehicular cloud computing

2.4.4 Impacts on Operations

With the increasing prevalence of smart driving technologies, a series of operational strategies can be improved or developed, which include the following:

- **Intersection Signal Control:** With full automation and V2V communication, it is possible to change the paradigm of current signal control, which is queue-based. Instead, the intersection's signal equipment can respond to upcoming flow on a vehicle basis. Simulation studies show that up to a 90% improvement in throughput can be attained. Even without the automation, V2I communication can facilitate transit priority and automatic vehicle location applications, which are both ready to implement in the near future.
- **Freeway Metering:** The primary purpose of freeway metering is to prevent traffic congestion on freeways by maintaining smoother and safer merging patterns. With V2V communication and blind spot monitoring features, the merging is anticipated to be accomplished via cooperation between the individual vehicles' systems.
- **Managed Lanes:** Managed lanes can be used to incentivize the use of smart driving technologies, and create the environment for platooning vehicles, which are equipped with the CACC. This will improve travel time and travel time reliability for corresponding travelers.
- **Traveler Information:** Smart driving vehicles with connectivity (DSRC or cellular) will be able to receive navigation, signal, and traffic information more effectively, which will reduce the needs of roadside message signs. Also, through disseminating information strategically, it is possible to use the road resources more effectively, respond faster to demand variations, and thus mitigate congestion.

- **Road Weather Management**: Smart driving vehicles can sense weather changes and send such information to traffic management centers (TMC) via roadside devices. This allows more accurate and reliable sensing of weather information and identification of weather-sensitive hotspots.
- **Tolling:** With the DSRC module, tolling will become easier to implement, reducing dependency on RFID (radio-frequency identification) devices, camera/image processing, or manual operations at tolling stations.
- **Work Zone Management:** Work zone safety is a big concern. Smart driving vehicles will allow construction zone information to be more effectively disseminated upstream of the work zone, and allow vehicles to pass through obstructions without harming workers.
- **CV-enabled Traffic Management:** CV-enabled traffic management is the result of the evolution of regular TMCs that have undergone changes allowed by the availability of "big data". TMCs of the future will need to increase their ability to be proactive, responsive, and adaptable, as well as being appropriately supported, in order to serve increasingly dynamic transportation networks.
- **Shared Vehicle Mobility:** Level 4 AVs can enable shared mobility, which will alter the vehicle ownership model and change the fleet composition in the long run. This can save parking space in urban areas and reduce the cost of traveling.
- **Auto-valet Parking:** This feature allows a driver to tell the vehicle to go park itself through an application on a smart device. The driver will receive notification when the vehicle has parked itself. This feature will save drivers time as the vehicle finds parking on its own. With reduced cruise time searching for a parking space, emissions will be reduced.

Chapter 3 details the project surveys that were undertaken during this research project.

Chapter 3. Project Surveys

Two surveys were undertaken to estimate fleet-wide adoption of CAV technologies in the long term, i.e., 2015–2045 (Bansal & Kockelman, 2015). In a national survey (termed *U.S. Survey*), eight scenarios were created based on technology prices (using 5% and 10% annual reduction rates), willingness to pay (WTP) (at 0%, 5%, and 10% annual increment rates), and regulations (specifically, those on electronic stability control [ESC] and connectivity). The survey investigated each respondent's current household vehicle inventory, their technology adoption, future vehicle transaction decisions, WTP for and interest in CAV technologies, and autonomous vehicle (AV) use based on trip types, travel patterns, and demographics. These simulations can help predict trends, such as the proportion of households that have a fully AV by 2030. The survey questions can be found in Appendix A.

The second, Texas-based survey (*Tx Survey*), examined a variety of perception and attitude analyses using various econometric models (Bansal & Kockelman, 2015). Response variables include respondents' interest in and WTP for connectivity, WTP for different levels of automation, adoption timing of AVs, adoption rates of shared AVs (SAVs) under different pricing scenarios, home location decisions after AVs become a common travel mode, and support for road-tolling policies (to avoid excessive demand from easier travel). Respondents' home locations were also geocoded to account for the impact of built-environment factors (e.g., population density and local population below poverty line) on the households' WTP for and opinions about CAV technologies, as well as vehicle transaction and technology adoption decisions. Subsequently, person- and household-level weights were calculated and used to obtain relatively unbiased estimates of summary statistics, model estimates, and technology adoption rates. The survey questions can be found in Appendix B.

Estimating a household's WTP for CAV technologies is useful in identifying the demographic characteristics and land use settings of both early and late adopters. Such information helps policymakers and planners predict near-term to long-term adoption of CAV technologies and devise policies to promote optimal adoption rates.

While AVs are set to emerge on the public market, they may quickly offer another mode of transportation: shared AVs (SAVs). SAVs offer short-term, on-demand rentals with self-driving capabilities, like a driverless taxi (Kornhauser et al. 2013, Fagnant et al. 2015). SAVs may overcome the limitations of current carsharing programs, such as vehicle availability, because travelers will have the flexibility to summon a distant SAV. Several studies (e.g., Burns et al. 2013, and Fagnant and Kockelman 2014) have shown how SAVs may reduce average trip costs by 30% to 85%, depending on the cost of automation and expected returns on the fleet operator's investment. Fagnant and Kockelman's (2015) agent-based simulation concluded that dynamic ridesharing (DRS) has the potential to further reduce total service times (wait times plus in-vehicle travel times) and travel costs for SAV users, even after incorporating extra passenger pick-ups, drop-offs, and indirect routings. Chen et al. (2015) extended some of that work, and examined the performance (including profitability) of a fleet of shared electric AVs across a 100- mile by 100-mile region. Pivoting off those simulations, this study explores the factors affecting SAV adoption rates under three pricing scenarios: $1, $2, and $3 per occupied-mile traveled.

After AV adoption by neighbors and friends, individuals may gain confidence in such vehicles and/or sense social pressure, prompting them to purchase such technologies. Thus, this study estimates the adoption timing of AVs (e.g., will the respondent "never adopt" an AV, wait until 50% of his/her friends adopt an AV, wait for just 10% of his/her friends adopt one, or try to obtain an AV as soon as such vehicles are available in the market).

More efficient use of travel time (by allowing work or cell-phone conversations, for example) while riding in AVs may encourage individuals to shift their home locations to more remote locations, to enjoy lower land prices (and thereby bigger homes or parcels). Thus, AVs can exacerbate urban sprawl and increase a region's vehicle-miles traveled (VMT). However, a high density of low-cost SAVs in downtown areas may counteract such trends. Given the major land use shifts that could occur, this study also explores the factors associated with residential shifts, as motivated by AV and SAV access.

Reliable availability of low-cost SAVs (with an option of DRS) may increase the shared vehicle market and reduce private-vehicle ownership. However, such high levels of service may induce demand for more VMT (Anderson et al. 2014). Tolling policies can moderate such rebound and congestion potential. Thus, this study also explores the factors affecting individuals' opinions about tolling policies.

3.1 U.S. Survey

The U.S. Survey's fleet evolution simulation results indicate that around 98% of the U.S. vehicle fleet is likely to have ESC and connectivity in years 2025 and 2030, respectively, under the National Highway Traffic Safety Administration's (NHTSA) current and probable regulations. These regulations are likely to accelerate adoption of these technologies by 15 to 20 years, and make U.S. roads safer. At more than a 5% WTP increment rate and 5% price reduction rate, all Level 1 technologies are estimated to have adoption rates of more than 90% in 2045. Among Level 1 technologies, traffic sign recognition (TSR) is the least interesting for Americans (54.4% of respondents reported $0 WTP). It is currently the least adopted (2.1%), and is anticipated to remain that way, with adoption rates of 38.1% in 2045 at 5% tech-price reduction and constant WTP. At 5% price reduction and 5% WTP increment rate, however, TSR is estimated to be the fourth-least adopted, with adoption rates of 70%. Blind-spot monitoring and emergency automatic braking are the two most interesting Level 1 technologies for Americans; they are anticipated to be the most and second-most adopted Level 1 technologies (excluding ESC) in 2045 at 5% tech-price reduction and constant WTP, with adoption rates of 53.5% and 51.2%. However, blind-spot monitoring and emergency automatic braking are anticipated to be the third-most and most adopted Level 1 technologies in 2045 at 5% price reduction and 5% WTP increment rate, with adoption rates of 73.6% and 77.8%.

More than half of the respondents are not willing to pay anything to add the advanced automation technologies (self-parking valet, and Level 3 and Level 4 automation). Thus, the population-weighted average WTP to add these technologies is less than half of the average WTP of the respondents who indicate non-zero WTP for these technologies. Of all the respondents, the average WTP to add connectivity and Level 3 and Level 4 automation are $67, $2,438, and $5,857, respectively. (And these values roughly double if one only averages the respondents who provide a non-zero WTP value.) Long-term fleet evolution suggests that Level 4 AVs are likely to represent 24.8% to 87.2% of the U.S. vehicle fleet in 2045[1].

The U.S. Survey's opinion-related summaries indicate that around 88.2% of Americans believe that they are great drivers and, surprisingly, around three-quarters enjoy driving a car.

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[1] Lower bound on adoption rate is anticipated at *5% drop in tech prices and constant WTP* and upper bound is forecasted at *10% drop in tech prices and 10% WTP*.

Around 60% of the respondents would be uncomfortable sending AVs out knowing that, as owners, they would be liable for any accident. The topic of greatest discomfort for Americans is allowing their vehicle to transmit data to toll operators and insurance companies. Technology companies (62.3%), followed by luxury vehicle manufactures (49.5%), appear to be the top choices of Americans for developing Level 4 AVs. Roughly the same shares of respondents reported WTP of $0 to use AVs for either short-distance (42.5%) or long-distance (40.0%) trips. The average number of long-distance trips (over 50 miles) is reported to increase by 1.3 (per person per month) due to the adoption of AVs.

3.2 Texas Survey

The results of the Tx Survey suggest that around 41% of Texans are not ready to use SAVs and only 7.3% hope to rely entirely on an SAV fleet, even at $1 per mile. AVs and SAVs are less likely to affect Texans' decisions about moving closer to or farther from the city center: about 81.5% indicated a desire to stay at their current location. Talking to other passengers and looking out the window are Texans' top two activity picks while riding in Level 4 AVs. Affordability and equipment failure are Texans' top two concerns regarding AVs; the two least concerning aspects are learning how to use AVs and, surprisingly, potential privacy breaches. Texans expect that AVs can help provide better fuel economy and also decrease crashes: 53.9% and 53.1% of the respondents, respectively, indicated that these benefits will be very significant.

Texans' average WTP to save 15 minutes of travel time on a 30-minute one-way trip is $6.80, but this figure increases to $9.50 if we remove those respondents with $0 WTP for this benefit (28.5%). The average WTP to ride in Level 4 AVs alone on a one-way trip, among those with positive WTP, are $9.90, $10.10, and $18.10 for shopping, work, and intercity trips, respectively, and these WTPs increase to $11.80, $13.60, and $20.40 for a ride with family. Texans are most likely to support adaptive traffic signal timing and least likely to support real-time adjustment in parking prices (when 80% of vehicles are connected). On average, Texans rank safety as the most important and climate change as the least important area of improvement in automobile technologies.

Using Tx Survey's data, ordered probit (OP) and interval regression (IR) models were estimated to understand the impact of Texans' demographics, built-environment factors, travel characteristics, and other attributes on their adoption of and interest in CAV technologies and SAVs. Those who support speed regulation strategies (e.g., speed governors on all new vehicles) and have higher household income (other attributes held constant) are estimated to pay more for all levels of automation and connectivity. However, older and more experienced licensed drivers are expected to place lower value on these technologies. Perhaps older individuals are finding it difficult to conceive that CAVs are about to hit the roads, and licensed drivers who particularly enjoy driving might be worried about sacrificing those elements of driving they find enjoyable. Caucasians' WTP for Level 2 automation and SAV adoption rates are estimated to be lower than other ethnicities, as was the case for connectivity, implying that non-Caucasians are likely to be early adopters of these technologies. Interestingly, the AV adoption timing of those respondents who reported higher WTP for AVs is less likely to depend on friends' adoption rates. It is worth noting that even unemployed and lower income households (with annual household income less than $30,000) are estimated to use SAVs more frequently at $1 per mile; perhaps SAVs are affordable for these individuals at this price. Respondents who are familiar with UberX are estimated to use SAVs less frequently at $2 and $3 per mile (more than what carsharing companies and UberX charge). Perhaps those who know about ridesharing services are not willing to pay additional costs to enjoy SAVs' additional utilities (on the top of traditional ridesharing). Bachelor's degree holders, single individuals, and full-time workers who support speed governors, own at least a vehicle with Level 2 automation, have experienced more fatal crashes in the past, and live farther from a city center (all other attributes held constant) are likely to move closer to the city center. Perhaps these individuals are excited about higher density of low-cost SAVs near the city center.

These results reflect the current perceptions of Americans (and more explicitly, of Texans). As the public learns more about CAVs and more people gain familiarity with these technologies, these perceptions and potential behavioral responses are apt to change, in some cases rapidly and dramatically. Integration of household evolution over the years, followed by behaviorally defensible temporal variation in the households' WTP, can change the estimates of the technology adoption rates. This is a potential future research direction. Lastly, SAVs are likely to change future vehicle ownership patterns; thus, their inclusion in the simulation framework can be a good extension of this study.

Section 3.3 discusses recent literature on public opinions about CAV technologies and previously proposed frameworks to forecast the adoption of new technologies. Sections 3.4 and 3.5 are based on the U.S. Survey and include questionnaire design, data acquisition, sample correction, geocoding, summary statistics of key variables, a simulation framework to forecast the long-term adoption of CAV technologies, and results of the 30-year forecast under different technology pricing, WTP scenarios, and NHTSA regulation scenarios. Section 3.6 focuses on the Tx Survey and consists of survey design and data processing, dataset statistics, and various behavioral model specifications. Section 3.7 concludes with recommendations and ideas for further research.

3.3 Literature Review

Successful implementation of CAV technologies will require public acceptance and adoption of these technologies over time. In recent years, many researchers and consulting firms have conducted surveys and focus groups to understand the public perceptions of CAV benefits and limitations. This section summarizes the key findings of all these public opinion surveys. These studies provide descriptive statistics regarding public awareness, concerns, and expected benefits of smart-vehicle technologies. However, none of them offered forecasts of the long-term adoption of CAV technologies. This section also includes the previously-developed frameworks to forecast the long-term adoption of new technologies, such as plug-in hybrid electric vehicles (PHEV).

3.3.1 Public Opinion Surveys about Adoption of CAVs

Casley et al. (2013) conducted a survey of 467 respondents to understand their opinions about AVs. The results indicate that approximately 30% of respondents were willing to spend more than $5,000 to adopt full automation in their next vehicle purchase and around the same proportion of respondents showed interest in adopting AV technology four years after its introduction in the market. Eighty-two percent of respondents reported safety was the most important factor affecting their adoption of AVs, while 12% said legislation, and 6% said cost.

Begg (2014) conducted a survey of over 3,500 London transport professionals to understand their expectations and issues related to the growth of driverless transportation in London. Eighty-eight percent of respondents expected Level 2 vehicles to be on the road in the U.K. by 2040; 67% and 30% believe the same for Level 3 and Level 4 vehicles, respectively.

Furthermore, approximately 60% of respondents supported driverless trains in London, and the same proportion of respondents expected AVs to be safer than conventional vehicles.

Kyriakidis et al. (2014) conducted a survey of 5,000 respondents across 109 countries by means of a crowd-sourcing internet survey. The results indicate that respondents with higher VMT and who use the automatic cruise control feature in their current vehicles are likely to pay more for fully AVs. Approximately 20% of respondents showed a WTP of more than $7,000 for Level 4 AVs, and approximately the same proportion of respondents did not want to pay more to add this technology to their vehicle. Most importantly, 69% of respondents expected that fully AVs are likely to gain 50% market share by 2050.

Schoettle and Sivak (2014a) surveyed 1,533 respondents across the U.K., the U.S., and Australia to understand their perceptions of AVs. Results indicate that approximately two-thirds of respondents had previously heard about AVs. When respondents were asked about the potential benefits of Level 4 AVs, 72% expected fuel economy to increase, while 43% expected higher travel time savings. Interestingly, 25% of respondents were willing to spend at least $2,000 to add full self-driving automation in the U.S., while the same proportion of respondents in the U.K. and Australia were willing to spend $1,710 and $2,350, respectively. However, around 55% of respondents in each country did not want to pay more to add these technologies. When asked about their potential activities while riding in Level 4 AVs (e.g., working, reading, and talking with friends), the highest proportion of respondents (41%) said they would watch the road even though they would not be driving. The results of one-way analysis of variance indicated that females are more concerned about AV technologies than males.

Underwood (2014) conducted a survey of 217 experts. Eighty percent of respondents had a master's degree, 40% were AV experts, and 33% were CV experts. According to these experts, legal liability is the greatest barrier to fielding Level 5 AVs (full automation without steering wheel), and consumer acceptance is the smallest. Approximately 72% of the experts suggested that AVs should be at least twice as safe as the conventional vehicles before they are authorized for public use. Fifty-five percent of the experts indicated that Level 3 AVs are not practical because drivers could become complacent with automated operations and may not take required actions.

CarInsurance.com's survey of 2000 respondents found that approximately 20% were interested in buying AVs (Vallet 2013). Interestingly, when respondents were presented with an 80% discount on car insurance for AV owners, 34% and 56% of respondents indicated strong and moderate interest in buying AVs, respectively. When respondents were asked to choose the activities they would like to perform while riding in AVs, the highest share of respondents (26%) chose to talk with friends. Survey results also indicate that approximately 75% of respondents believed that they could drive more safely than AVs. Only 25% would allow their children to go school in AVs, unchaperoned. When asked who they would trust most to deliver the AV technology, the highest proportion (54%) of respondents said traditional automobile companies (e.g., Honda, Ford, and Toyota), instead of other companies (e.g., Google, Microsoft, Samsung, and Tesla). Seapine Software's (2014) survey of 2,038 respondents indicated that approximately 88% (84% of 18- to 34-year-olds and 93% of 65-year-olds) were concerned about riding in AVs. Seventy-nine percent of respondents were concerned about equipment failure, while 59% and 52% were concerned about liability issues and hacking of AVs, respectively.

J.D. Power (2012) conducted a survey of 17,400 vehicle owners before and after revealing the market price of 23 CAV technologies. Prior to learning about the market price, 37% of respondents showed interest in purchasing the AV technology in next vehicle purchase, but that number fell to 20% after learning that this technology's market price is $3000. The 18- to 37-year-old male respondents living in urban areas showed the highest interest in purchasing AV technology. Their recent survey (J.D. Power, 2015) of more than 5,300 consumers who had recently acquired a new car revealed that younger generations have higher preferences for advanced automation technologies, while older generations tend to prefer basic Level 1 technologies. Among the most preferred technologies across all the respondents were blind-spot monitoring and night vision.

A KPMG (2013) focus group study, using 32 participants, notes that respondents became more interested in AVs when they were provided incentives like a designated lane for AVs, and learned that their commute time would be cut in half. In contrast to Schoettle and Sivak's (2014a) findings, the focus group's discussion and participants' ratings for AV technology suggests that females are more interested in these technologies than males. While focus-group females emphasized the benefits of AVs (e.g., mobility for physically challenged travelers), males were more concerned about being forced to follow speed limits. Interestingly, the oldest participants (60 years old+) and the youngest (21 to 34 years old) expressed the highest WTP in order to obtain automation technologies. Continental (2015) surveyed 1,800 and 2,300 respondents in Germany and the United States, respectively. Approximately 60% of respondents expected to use AVs in stressful driving situations, 50% believed that AVs can prevent accidents, and roughly the same number indicated they would likely engage in other activities while riding in AVs.

Recently, Schoettle and Sivak (2014b) surveyed 1,596 respondents across the U.K., the U.S., and Australia to understand their perceptions of CVs. Surprisingly, only 25% of respondents had heard about CVs. When asked about the expected benefits of CVs, the highest proportion of respondents (85.9%) expected fewer accidents and the lowest proportion (61.2%) expected less distraction for the driver. Approximately 84% of respondents rated safety as the most important benefit of CVs, 10% said mobility, and 6% said environmental benefits. Interestingly, 25% of respondents were willing to spend at least \$500, \$455, and \$394 in the U.S., the U.K., and Australia, respectively, to add CV technology. However, 45.5%, 44.8%, and 42.6% of respondents did not want to pay anything extra to add these technologies in the U.S., the U.K., and Australia, respectively.

3.3.2 Anticipating Long-Term Adoption of New Technologies

Vehicle transaction models and simulation frameworks have been increasingly used for forecasting market shares of alternative fuel vehicles (Paul et al. 2011). However, these models are not directly applicable to forecasting the long-term adoption of CAV technologies, but provide a good basis for this new framework. Musti and Kockelman (2010) proposed a vehicle fleet evolution framework to forecast PHEV's and HEV's shares in Austin, Texas, over a 25- year period. They developed a microsimulation framework based on a set of interwoven models (vehicle transaction, vehicle choice, and vehicle usage) for vehicle ownership along with greenhouse gas (GHG) emissions forecasts in Austin. They estimated Austin's highest future PHEV-plus-HEV share (19% by 2034) under a feebate policy scenario. Paul et al., (2011) adopted a similar microsimulation framework to forecast the U.S. vehicle fleet's composition and associated GHG emissions, from 2010 to 2035, under a variety of policy, technology, and gas-price scenarios. Paul et al. (2011) predicted 14.8% as the highest (total) predicted share of PHEV-plus-HEV by 2035, under the gas price of \$7 per gallon.

3.4 Forecasting Americans' Long-Term Adoption of Automation and CV Technologies

3.4.1 Survey Design and Data Processing

Questionnaire Design and Data Acquisition

The team designed and disseminated a U.S.-wide survey in June 2015 using Qualtrics, a web-based survey tool. The Survey Sampling International's (SSI, an internationally recognized and highly professional survey firm) continuous panel of respondents served as the respondents for this survey. The Office of Research Support at The University of Texas at Austin processed this study and determined it as "Exempt" from Institutional Review Board[2] (IRB) review (protocol number: 2014-09-0078).

Exploring respondents' preferences for the adoption of emerging vehicle and transport technologies, the survey asked 58 questions, divided into 6 sections. The survey asked respondents about their household's current vehicle inventory (e.g., odometer reading and average miles traveled per year), vehicles sold in the past 10 years, future vehicle preferences (e.g., buying or selling a vehicle, or only adding technology to the existing vehicles), and WTP for various CAV technologies. Respondents were also asked for their opinions related to CAVs (e.g., comfort in allowing vehicle to transmit data to various agencies and the appropriate developers for Level 4 AVs), travel patterns (e.g., using AVs for the long-distance trips and increase in frequencies of long-distance trips due to AVs), and demographics.

Data Cleaning and Sample Correction

A total of 2,868 Americans (including 1,762 Texans) completed the survey, but after removing the fast responses and conducting some sanity checks[3], 2,167 responses (1,364 Texans) remained eligible for further analysis. The sample over-represented Texans and specific demographic classes, such as female and bachelor's degree holders, and under-represented others, such as men who did not complete high school and males 18 to 21 years old. Therefore, the survey sample proportions in 120 categories[4] (2 gender-based, 5 age-based, 6 educational-attainment groups, and "respondent is Texan or not?") were scaled using the 2013 American Community Survey's Public Use Microdata Sample (PUMS 2013). These scale factors were used as person-level weights to un-bias person-related summary statistics (e.g., binary opinion regarding whether AVs are realistic or not) and model-based parameter estimates. Similarly, some household groups were under- or over-represented. Thus, household weights were calculated for 130 categories[5] (4 household size groups, 4 household workers groups, 5 vehicle ownership groups, and "household

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[2] IRB reviews research studies to minimize the risks for human subjects, ensure all subjects give their consent and receive full information about risks involved in the research, and promote equity in human subject research.

[3] Respondents who completed the survey in less than 13 minutes were assumed to have not read questions thoroughly, and their responses were discarded. Certain other respondents were considered ineligible for further analysis: those younger than 18 years, reporting more workers or children than represented in the household size, having a very old car with all technologies, reporting the same distance of their home from various places (airport and city center, for example), and providing other combinations of conflicting answers.

[4] Out of 120 categories, 4 were missing in the sample, and were merged with adjacent categories.

[5] There are 160 combinations of traits (4 x 4 x 5 x 2 = 160), but there are only 130 categories because some of the categories cannot exist. For example, the number of workers cannot exceed household size. Out of 130 categories, 12 were missing in the sample, and were merged with adjacent categories.

is Texan or not?") using PUMS 2013 data. These household weights were used to un-bias household-related (e.g., WTP for new technologies and vehicle transaction decisions) model estimates and summary statistics.

3.4.2 Geocoding

To understand the spread of survey respondents across the U.S. and to account for the impact of built-environment factors (e.g., population density and population below poverty line) on household vehicle transaction and technology adoption decisions, the respondents' home addresses were geocoded using Google Maps API and spatially joined with U.S. census-tract- level shape files using open-source Quantum GIS. For respondents who did not provide their street address or recorded incorrect addresses, their internet protocol (IP) locations were used as the proxies for their home locations. Figure 3.1 shows the geocoded respondents, with most respondents living in the southern and eastern U.S.

3.4.3 Dataset Statistics

These data offer many valuable and straightforward summary statistics, regarding interest in, WTP for, and opinions on a wide array of technologies.

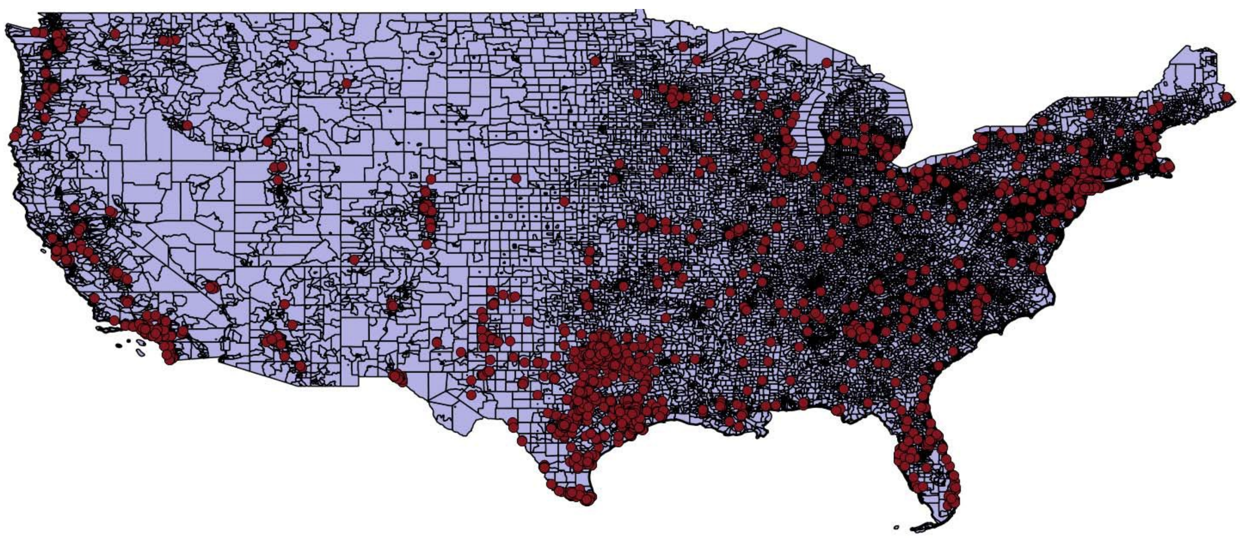

Figure 3.1: Geocoded respondents across continental U.S.

3.4.4 Interest in Level 1 and Level 2 Technologies

Table 3.1 summarizes WTP for, interest in, and current adoption of Level 1 and Level 2 automation technologies[6]. As shown in Figure 3.2, respondents showed the least interest in TSR and left-turn assist (LTA) technologies. TSR is of no interest to 52.6% of the respondents, and 54.4% noted they are unwilling to pay anything to add this technology to their vehicles. LTA is slightly more acceptable: 46.9% of the respondents are not interested in it, and 46.1% would not be willing to pay anything for it. Blind-spot monitoring and emergency automatic braking appear

[6] Level 1 and Level 2 automations are considered together and used interchangeably at a few places, since a combination of Level 1 technologies leads to Level 2 automation.

to be the two most appealing technologies for Americans. Around half (50.7%) of the respondents are very interested in blind-spot monitoring, only 17.3% are not interested in it, and the smallest proportion of the respondents (only 23.7%) indicate \$0 WTP for it. Emergency automatic braking is the second most interesting technology for Americans, with 45.8% of the very-interested respondents, only 22.8% of the not-interested respondents, and only 28.7% of the respondents with \$0 WTP.

Not surprisingly, among these Level 1 and Level 2 automation technologies, ESC is the one most expected to be already present in the respondents' vehicles: 21.6% of those who have a vehicle reported having this technology in at least one household vehicle, and it is possible that many respondents are unaware that their vehicles now come equipped with such technology (since ESC has been mandated on all new passenger vehicles in the U.S. since 2012 model year [NHTSA 2012]). The second most adopted technology is ACC, with 12.8% of the respondents (who have at least one vehicle) having already adopted this technology. The least adopted technology is TSR, as it is present in only 2.1% of the respondents' vehicles, while pedestrian detection has a slightly higher rate of adoption, at 3.3%.

The respondents' WTP for Level 1 and Level 2 technology varies significantly[7]. The average WTP (among the respondents who are willing to pay some positive amount for the technology) to add ESC to an existing or a future vehicle exceeded the projected price after 5 years: \$79 (see Table 3.2[8]) versus \$70. For every other technology, the average WTP (of the respondents who are ready to pay for the technology) is lower than the estimated future price after five years. For example, average WTP to add emergency automatic braking is \$257 (versus \$320, the projected price after five years) and for blind-spot monitoring, it is \$210 (versus \$280). The worst ratio of the average WTP to the projected price is for the adaptive headlights: \$345 versus \$700. Respondents value this technology significantly; in fact, it is the second most valued technology in terms of average WTP (of the respondents who are ready to pay for the technology), but respondents probably believe that the projected price is still too high.

[7] Before asking a WTP question, respondents were provided with a price forecast for a particular technology. For example, the price forecast for ESC was "Current Price: \$100; Price after 5 years: \$70; Price after 10 years: \$50." It is difficult to estimate the price of a particular Level 1 or Level 2 technology, since these technologies are provided in packages. For example, BMW provides a \$1900 package with lane departure warning, forward collision braking, ACC, pedestrian detection, and blind-spot monitoring. Thus, after analyzing different packages, current prices for each of these technologies were determined. Subsequently, a 30% price reduction in the next 5 years and a 50% price reduction in the next 10 years were considered (with 7% annual price reduction rate) to provide future price estimates of these technologies.

[8] Table 3.2 demonstrates average WTP for CAV technologies. The second column represents average WTP of all respondents, and the third column summarizes the WTP of those who indicated a WTP more than \$0 for a specific technology.

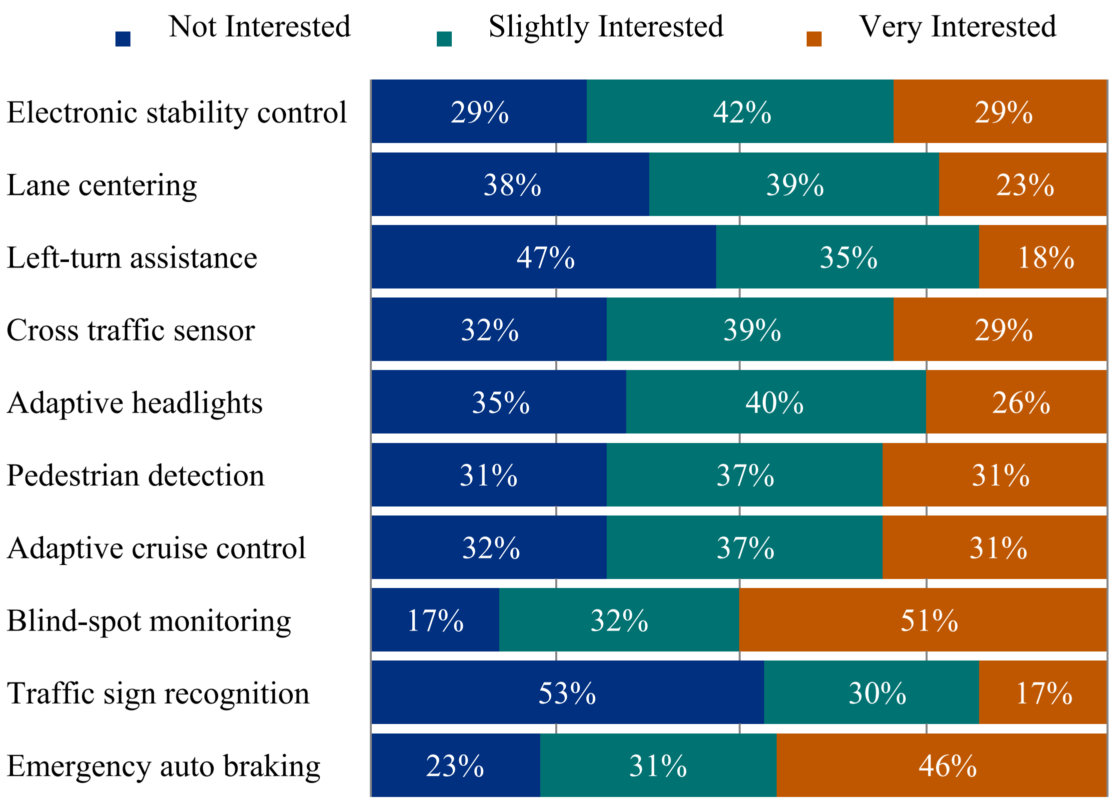

Figure 3.2: Interest in automation technologies

Table 3.1: Population-weighted summaries for Level 1 and Level 2 technologies

Response Variables	Percentages	Response Variables	Percentages
Electronic Stability Control			
Willingness to Pay to Add		*Present in a Vehicle**	
Do not want to pay anything	33.4%	Yes	21.6%
Less than $60	16.8%	*Interested in Technology*	
$60 to $79	20.4%	Not interested	29.1%
$80 to $119	21.6%	Slightly interested	41.6%
$120 and more	7.8%	Very interested	29.3%
Lane Centering			
Willingness to Pay to Add		*Present in a Vehicle**	
Do not want to pay anything	41.7%	Yes	3.9%
Less than $200	21.4%	*Interested in Technology*	
$200 to $399	14.2%	Not interested	37.8%
$400 to $599	12.4%	Slightly interested	39.0%
$600 and more	10.3%	Very interested	23.2%
Left-Turn Assist			
Willingness to Pay to Add		*Present in a Vehicle**	
Do not want to pay anything	46.1%	Yes	3.8%
Less than $100	14.9%	*Interested in Technology*	
$100 to $299	23.6%	Not interested	46.9%
$300 to $399	8.1%	Slightly interested	35.3%
$400 and more	7.3%	Very interested	17.8%
Cross Traffic Sensor			
Willingness to Pay to Add		*Present in a Vehicle**	
Do not want to pay anything	32.8%	Yes	9.6%
Less than $100	15.2%	*Interested in Technology*	
$100 to $199	14.4%	Not interested	31.7%
$200 to $399	24.6%	Slightly interested	38.9%
$400 and more	13.0%	Very interested	29.3%
Adaptive Headlights			
Willingness to Pay to Add		*Present in a Vehicle**	
Do not want to pay anything	41.1%	Yes	9.5%
Less than $150	17.7%	*Interested in Technology*	
$150 to $349	17.4%	Not interested	34.7%
$350 to $649	15.2%	Slightly interested	39.6%
$650 and more	8.7%	Very interested	25.6%

Response Variables	Percentages	Response Variables	Percentages
Pedestrian Detection			
Willingness to Pay to Add		*Present in a Vehicle**	
Do not want to pay anything	37.5%	Yes	3.3%
Less than $100	16.0%	*Interested in Technology*	
$100 to $199	12.8%	Not interested	31.4%
$200 to $399	24.2%	Slightly interested	37.1%
$400 and more	9.5%	Very interested	31.5%
Adaptive Cruise Control			
Willingness to Pay to Add		*Present in a Vehicle**	
Do not want to pay anything	37.7%	Yes	12.8%
Less than $150	26.2%	*Interested in Technology*	
$150 to $249	14.8%	Not interested	32.1%
$250 to $349	11.9%	Slightly interested	37.1%
$350 and more	9.4%	Very interested	30.8%
Blind-spot Monitoring			
Willingness to Pay to Add		*Present in a Vehicle**	
Do not want to pay anything	23.7%	Yes	9.9%
Less than $150	29.5%	*Interested in Technology*	
$150 to $249	18.2%	Not interested	17.3%
$250 to $349	14.7%	Slightly interested	31.9%
$350 and more	13.9%	Very interested	50.7%
Traffic Sign Recognition			
Willingness to Pay to Add		*Present in a Vehicle**	
Do not want to pay anything	54.4%	Yes	2.1%
Less than $100	15.0%	*Interested in Technology*	
$100 to $199	9.6%	Not interested	52.6%
$200 to $299	10.1%	Slightly interested	30.1%
$300 and more	10.9%	Very interested	17.3%
Emergency Automatic Braking			
Willingness to Pay to Add		*Present in a Vehicle**	
Do not want to pay anything	28.7%	Yes	5.4%
Less than $200	26.8%	*Interested in Technology*	
$200 to $299	18.3%	Not interested	22.8%
$300 to $399	13.7%	Slightly interested	31.5%
$400 and more	12.4%	Very interested	45.8%
*Among the respondents who reported to have at least one vehicle in their households.			
(Number of Observations = 2,167)			

3.4.5 Connectivity and Advanced Automation Technologies

Table 3.2 summarizes respondents' WTP to add connectivity, self-parking valet system, and Level 3 and Level 4 automation. It is evident that more than half of the respondents are not ready to pay for any of the advanced automation technology, but comparatively fewer (39%) indicated $0 WTP to add connectivity. Among those who are willing to pay for advanced automation, the average WTP for Level 3 automation is $5,470 and for Level 4 automation, it is $14,196 (Table 3.3). Self-parking valet technology is valued at around $902 (with a simulation-projected price of $1,400 after 5 years, which may be too low [given how complex discerning a proper/legal parking spot can be in many settings]) and connectivity is valued at only $111 (projected price after five years is $140).

Table 3.2: Population-weighted WTP for adding connectivity and advanced automation technologies

Response Variables	Percentages	Response Variables	Percentages
WTP for Adding LV3 Automation		**WTP for Adding LV3 Valet Tech**	
Do not want to pay anything	55.4%	Do not want to pay anything	51.7%
Less than $2,000	13.3%	Less than $250	13.6%
$2,000 to $5,999	13.9%	$250 to $1,249	20.1%
$6,000 to $9,999	9.4%	$1,250 to $1,749	8.1%
$10,000 and more	7.9%	$1,750 and more	6.5%
WTP for Adding LV4 Automation		**WTP for Adding Connectivity**	
Do not want to pay anything	58.7%	Do not want to pay anything	39.1%
Less than $6,000	14.4%	Less than $75	20.3%
$6,000 to $13,999	10.3%	$75 to $124	16.5%
$14,000 to $25,999	9.3%	$125 to $174	11.6%
$26,000 and more	7.3%	$175 and more	12.5%
(Number of Observations =2,167)			

Table 3.3: Population-weighted average WTP for automation technologies

Average WTP for Adding Technology	For all Respondents	For those with WTP > 0
Electronic Stability Control	$52	$79
Lane Centering	$205	$352
Left-Turn Assist	$119	$221
Cross Traffic Sensor	$169	$252
Adaptive Headlights	$203	$345
Pedestrian Detection	$145	$232
Adaptive Cruise Control	$126	$202
Blind-spot Monitoring	$160	$210
Traffic Sign Recognition	$93	$204
Emergency Automatic Braking	$183	$257
Connectivity	$67	$111
Self-parking Valet	$436	$902
Level 3 Automation	$2,438	$5,470
Level 4 Automation	$5,857	$14,196
(Number of Observations =2,167)		

3.4.6 Opinions about CAV Technologies and Related Aspects

Table 3.4 summarizes respondents' opinions about their own behavior, automation technologies, and related aspects. Most Americans perceive themselves as good drivers (88.2%), enjoy driving a car (75.7%), and tend to wait before adopting new technologies (79.3%). Respondents are indecisive on the topic of whether AVs will drive better than them (one- third agrees, one-third disagrees, and final third has no opinion). Around 54.4% of respondents perceive AVs as a useful advancement in transportation, but 58.4% are scared of them. 23% of the respondents have been waiting for AV availability and only 19.5% will be comfortable sending an AV driving on its own, assuming that they as owners are liable for any accident it might cause. More than 41% of the respondents agree with the statement that AVs will be omnipresent in the future. Around 49% of the respondents think that AVs will function reliably, while 44% believe the idea of AVs is not realistic.

Table 3.4: Individual-weighted opinions of respondents

Opinions	Agree	Neutral	Disagree
I believe that I am a very good driver myself.	88.2%	9.3%	2.6%
I think AVs will drive more safely than my driving.	33.4%	31.6%	35.0%
Driving a car is something I enjoy.	75.7%	15.4%	8.9%
I generally tend to wait for a new technology if it proves itself.	79.3%	14.2%	6.5%
AVs are a useful advance in transportation.	54.4%	26.0%	19.7%
The idea of AVs is not realistic.	43.5%	26.8%	29.7%
AVs will be a regular mode of transport in 15 years.	41.4%	32.2%	26.4%
AVs scare me.	58.4%	19.4%	22.2%
I have waited a long time for AVs.	23.2%	23.8%	53.1%
I do not think that AVs will function reliably.	49.1%	29.8%	21.2%
I would be comfortable in sending my AVs out knowing that I am liable for an accident.	19.5%	19.9%	60.5%
(Number of Observations =2,167)			

Table 3.5 summarizes the respondents' opinions about their comfort in allowing their CVs to share information with certain organizations or other vehicles, as well as whom they trust to develop AVs. It is interesting to note that more than half of the respondents (50.4%) are comfortable if their vehicle transmits information to other vehicles, and 42.9% are comfortable sending information to the vehicle manufacturer. Respondents were most uncomfortable sending information to insurance companies (36.4%) and toll operators (33.3%).

The respondents mostly believe that AVs must be produced by technology companies (62.3%), and luxury vehicle manufacturers (49.5%). Mass-market manufacturers are in third place with support from 45.5% of the respondents. Around 7.9% of the respondents do not trust any company to manufacture AVs, and very few respondents (1.2%) are unsure.

Table 3.5: Individual-weighted opinions about connectivity and AVs' production

Comfortable in allowing a vehicle to transmit information to…	**Comfortable**	**Neutral**	**Uncomfortable**
Surrounding vehicles	50.4%	19.8%	29.8%
Vehicle manufacturers	42.9%	26.5%	30.6%
Insurance companies	37.0%	26.5%	36.4%
Transportation planners	40.9%	29.2%	30.0%
Toll operators	35.9%	30.9%	33.3%
To develop Level 4 AVs, I would trust:	**Percentage**		
Technology companies (e.g., Google, Apple, Microsoft, and Samsung)	62.3%		
Mass-market vehicle manufacturers (e.g., Toyota and Ford)	45.5%		
Luxury vehicle manufacturers (e.g., BMW and Mercedes)	49.5%		
Government agencies (e.g., NASA and DARPA)	1.4%		
Universities and research institutions	0.3%		
I would not trust any company to develop a Level 4 AVs.	7.9%		
Unsure	1.2%		
(Number of Observations =2,167)			

3.4.7 Opinions about AV Usage by Trip Types and Long-distance Travel

Table 3.6 demonstrates the respondents' opinions about AV use for different trip types and long-distance travel. Interestingly, around the same proportion of the respondents reported unwillingness to use AVs for short-distance (42.5%) or long-distance (40.0%) trips (over 50 miles). Around 40% of the respondents reported their willingness to use AVs in their everyday trips; however, only one-third of the respondents plan to use them for their or their children's school trips. In the context of long-distance travel, the highest proportion of the respondents (37.2%) plan to use AVs for trips with one-way distances between 100 and 500 miles. The respondents also believe their average number of long-distance trips will increase by 1.3 per month due to the adoption of AVs.

Table 3.6: Individual-weighted summaries for AV usage by trip type

I will use AVs during a…	**Percentage**	**I will use AVs for trips…**	**Percentage**
Work trip	41.1%	Between 50 and 100 miles	33.6%
School trip	33.3%	Between 100 and 500 miles	37.2%
Shopping trip	42.1%	Over 500 miles.	28.0%
Personal business trip	39.7%	I will not use AVs for such trips.	40.0%
Social or recreational trip	44.6%	**Average increase in the number of long-distance trips**	
I will not use AVs.	42.5%	Additional number of long-distance trips (per month)	1.3
(Number of Observations =2,167)			

3.5 Forecasting Long-Term Adoption of CAV Technologies

3.5.1 Simulation-based Framework

The simulation-based framework that forecasts the long-term adoption of CAV technologies consists of several stages, pursued together at a one-year time step. The first stage is a vehicle transaction and technology adoption model (as shown in Figure 3.4) that simulates the households' annual decisions to sell a vehicle ("sell"), buy vehicles ("buy"), sell a vehicle and buy vehicles ("replace"), add technology to the existing vehicles ("add technology"), and take no action ("do nothing"). A multinomial logit (MNL) model was estimated in BIOGEME (Bierlaire 2003) to determine the probabilities of making these decisions and use these probabilities in the Monte Carlo method to ascertain the vehicle transaction and technology adoption choice of each household after each year. Initial model specifications included all explanatory variables and the MNL model was re-estimated using stepwise elimination by removing the covariate with the lowest statistical significance. Although most of the explanatory variables enjoy a p-value greater than .05 (|z-stat| > 1.96), covariates with p-values lower than 0.32 (which corresponds to a |z-stat| of greater than 1.0) were also kept in the final specification. McFadden's R-Square and adjusted R-square are calculated to measure the models' goodness of fit (Figure 3.3).

McFadden's R-Square = $1 - \frac{log(L_{full})}{log(L_{null})}$ and McFadden's adjusted R-Square $= 1 - \frac{(log(L_{full})) - n}{log(L_{null})}$, where n is the number of parameters in the fitted model, and L_{full} and L_{null} denote the likelihood values of the fitted model and only-intercept (with no explanatory variable) model, respectively.

Figure 3.3: McFadden's R Square and Adjusted R-Square

In the case of a "sell" decision[9], the oldest vehicle (within a selling household) is disposed of. In the case of a "buy" decision, it is assumed that a household will buy (or lease) one or two vehicles, and that each vehicle can be acquired new or used. It is important to determine whether a household purchases a new or used vehicle, since it was assumed that Level 3 and Level 4 automation cannot be retrofitted into used vehicles and costs for retrofitting a self- parking valet system and Level 1/Level 2 automations into used vehicles are four times the cost of adding these technologies to new vehicles. Using the survey data, binary logit models were estimated in BIOGEME to determine these probabilities: 1) whether a household acquiring a vehicle will purchase one or two vehicles and 2) whether each vehicle will be new or used. These probabilities were used in Monte Carlo simulations.

Subsequently, connectivity is added to the purchased vehicle if a household's WTP for connectivity is more than its price. If the purchased vehicle is used, then Level 1 and Level 2 automations are added based on the household's total budget for Level 2 technologies, and preferences and WTP for each Level 2 technology (or Level 1 technology, if only one technology is added to the vehicle). As mentioned in Section 3.5.3, respondents were also separately asked about WTP for a self-parking valet system;[10] this option is added to the used vehicle if the

[9] It was assumed that the household sells or disposes of only one vehicle at a time.
[10] The self-parking valet system was not characterized in any level of automation, but was assumed to be present in any vehicle having Level 3 or Level 4 automation.

household's WTP is more than its price. If the purchased vehicle is new and the household's WTP for Level 4 automation is greater than the price of its addition, then Level 4 is added to the new vehicle. Otherwise a similar rule is checked for Level 3 automation. If the condition is met for Level 3, this automation is added to the new vehicle; otherwise a self- parking valet system and Level 1 and Level 2 automations are added to the new vehicle with the same rules as described for the used-vehicle case.

In the case of a "replace" decision, a household is assumed to first choose a "sell" option, followed by a "buy" decision. In the case of an "add technology" decision, if an existing vehicle already has Level 3 or Level 4 automations, then no new technology is added to the vehicle. If this is not the case, then the existing technologies in the vehicle are excluded from the choice set, and a self-parking valet system (if not present in the existing vehicle) and Level 1 and Level 2 automations are added to the existing vehicle with the same rules as described for the used- vehicle case. In the "do nothing" case, all vehicles are retained and no technology is added. If a household does not own a vehicle, but the simulation suggests it choose "sell", "replace", or "add technology" options, the household is forced to pick the "do nothing" option.

Finally, the population-weighted adoption rates of all technologies are extracted after each year.

This simulation framework does not consider the changes in household demographics over time (except the respondent's age and vehicle ownership, since they are explanatory variables in the vehicle transaction and technology adoption model). Integrating these additional household evolution models may improve estimates of CAV technologies' future adoption rates.

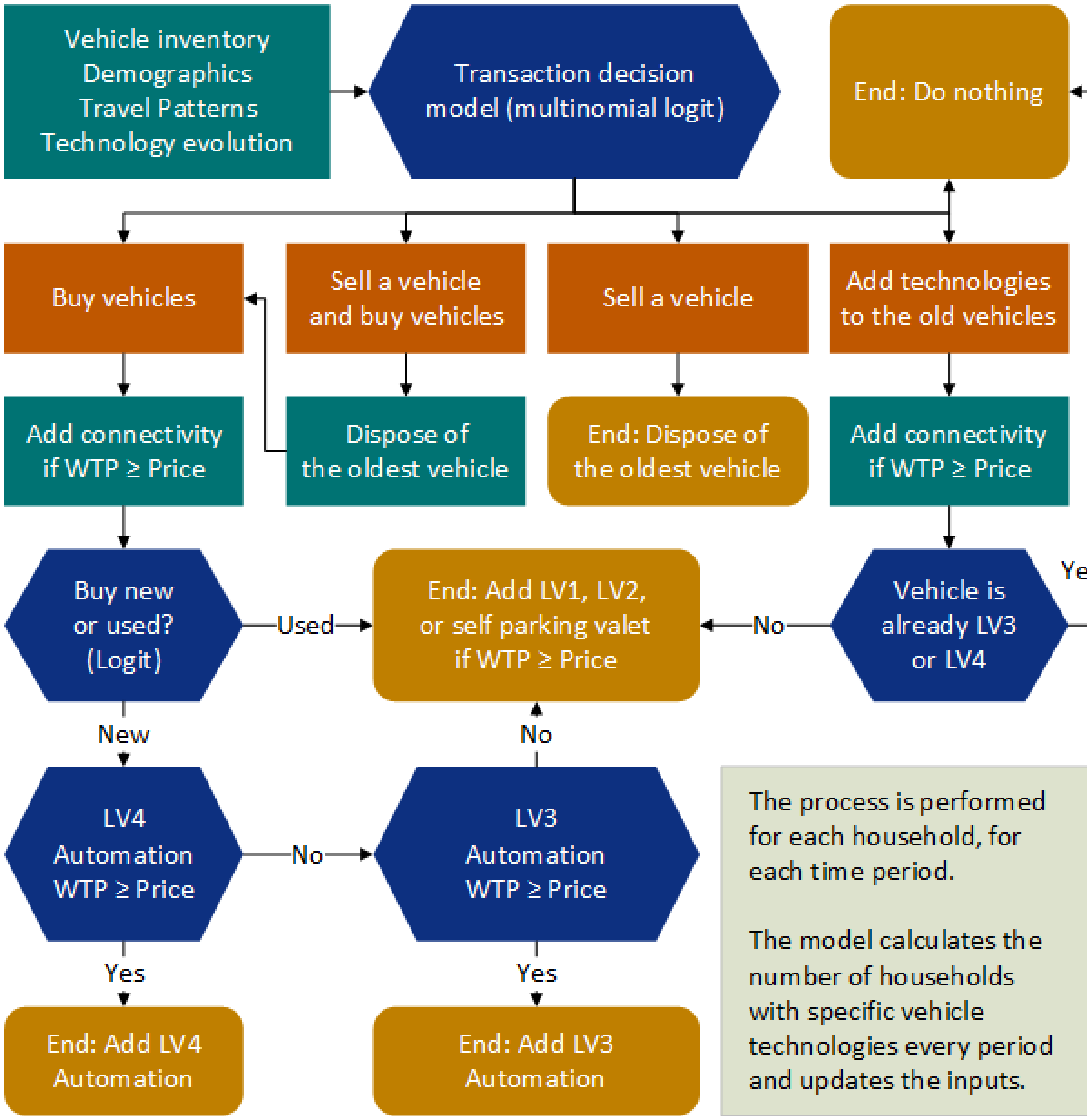

Figure 3.4: Simulation-based framework to forecast long-term technology adoption

3.5.2 Vehicle Transaction and Technology Adoption: Model Specifications

Table 3.7 summarizes (with population weights) person- and household-level variables, geocoded location variables, and transaction decision variables included in the vehicle transaction and technology adoption models.

Table 3.7: Population-weighted summary statistics of explanatory variables

Explanatory Variables	**Mean**	**SD**	**Min.**	**Max.**
Person Variables				
Age (years)	44.980	16.623	21	70
Male?	0.4897	0.5000	0	1
Single?	0.3358	0.4724	0	1
Bachelor's degree holder?	0.2561	0.4366	0	1
Full-time worker?	0.3146	0.4645	0	1
Have U.S. driver license?	0.9045	0.2940	0	1
Disabled?	0.1285	0.3348	0	1
Annual vehicle-miles traveled over 9,000 miles?	0.3971	0.4894	0	1
Retired?	0.1848	0.3882	0	1
Drive alone for work trips?	0.5151	0.4999	0	1
Household Variables				
More than 3 members in the household?	0.2553	0.4361	0	1
Number of workers in the household	1.1944	0.9220	0	7
More than 1 worker in the household?	0.3491	0.4768	0	1
Household income	64,640	51,924	5,000	250,000
Age of the oldest vehicle in the household (in years)	10.661	7.3239	0	30
Number of vehicles owned by the household	1.7828	1.0176	0	6
At least one vehicle in the household?	0.9292	0.2566	0	1
Number of vehicles sold in the past 10 years	0.4230	0.6651	0	5
At least one vehicle sold in the past 10 years?	0.3488	0.4767	0	1
Location Variables				
% of families below poverty line in the census tract	12.301	10.155	0	77
Employed and over 16 years of age (per square mile)	2,826.0	6,232.6	1.1917	1,13,187
Population density (per square mile)	3,958.8	8,680.4	1.6496	1,32,409
Distance to transit stop (from home) is greater than 3 miles?	0.4868	0.4999	0	1
Distance to downtown (from home) is greater than 5 miles?	0.6428	0.4793	0	1
Response Variables	**Mean**	**SD**	**Min.**	**Max.**
Transaction Decisions				
Sell	0.0382	0.1916	0	1
Replace	0.2406	0.4276	0	1
Buy	0.1639	0.3703	0	1
Add technology	0.0890	0.2848	0	1
Do nothing	0.4683	0.4991	0	1
Bought Two Vehicles?	0.0766	0.2659	0	1
Bought New Vehicle?	0.6495	0.4771	0	1
(Number of Observations =2,167)				

Table 3.8 shows the transaction model's final specification. The alternative specific constants (ASCs) indicate that, everything else being equal, households have inherent inclination and disinclination for "buy" and "replace" options. Specifically, older and single individuals with more than one worker in the household, who live farther from downtown in a financially poorer neighborhood (all other attributes remaining constant), are relatively less inclined towards selling their vehicles, but males with more vehicles in the household are likely more inclined to sell.

Bachelor's degree holders, full-time workers, and male respondents who drive alone for work, have more vehicles, and more than one worker in the household are more likely (everything else held constant) to replace a vehicle, but older respondents are less likely to make this decision. Older and single respondents whose households own more vehicles (all other attributes held constant) are less likely to buy vehicles. In contrast, respondents who drive alone to work, have more than three members and one worker in the household, and have older vehicles are more likely to buy vehicles. It is interesting to note that bachelor's degree holders who drive alone for work trips and live in neighborhoods with higher density of employed individuals are more inclined (everything else held constant) towards the "add technology" option than the "do nothing." However, all else being equal, older individuals who have older vehicles are likely to prefer the "do nothing" option over the "add technology."

Table 3.8: Transaction decisions (weighted multinomial logit model results)

Covariates	Coef.	T-stat
ASC_{Sell}	0	-fixed-
$ASC_{Replace}$	-1.810	-4.33
ASC_{Buy}	0.572	1.84
$ASC_{Add\ Technology}$	0	-fixed-
Sell		
Age (years)	-0.067	-10.15
Distance to downtown (from home) is greater than 5 miles?	-0.502	-2.06
Male?	0.686	2.64
Number of vehicles owned by the household	0.626	5.37
% of families below poverty line in the census tract	-0.020	-1.57
Single?	-0.884	-3.06
More than 1 worker in the household?	-0.833	-3.03
Replace		
Age (years)	-0.027	-6.29
Bachelor's degree holder?	0.556	4.93
Drive alone for work trips?	0.415	3.18
Full-time worker?	0.175	1.38
Male?	0.154	1.40
Number of vehicles owned by the household	0.127	1.84
At least one vehicle in the household?	1.440	3.65
Retired?	0.477	2.46
More than 1 worker in the household?	0.310	2.47
Buy		
Age (in years)	-0.039	-7.29
Drive alone for work trips?	0.172	1.30
More than 3 members in the household?	0.498	3.73
Age of the oldest vehicle in the household (in years)	0.016	1.73
Number of vehicles owned by the household	-0.283	-3.26
% of families below poverty line in the census tract	0.015	2.92
Retired?	0.265	1.22
Single?	-0.146	-1.03
More than 1 worker in the household?	0.171	1.25
Add technology		
Age (in years)	-0.041	-10.52
Bachelor's degree holder?	0.382	2.34
Drive alone for work trips?	0.438	2.71
Age of the oldest vehicle in the household (in years)	-0.033	-2.88
Employed and over 16 years of age (per square mile)	1.54E-05	2.11
Retired?	0.625	2.41
Fit statistics		
Null log-likelihood	-3487.65	
Final log-likelihood	-2688.66	
McFadden's R-square	0.229	
Adjusted R-square	0.220	
Number of observations	2,167	

Note: The "do nothing" option is base here.

Table 3.9 shows the "bought two vehicles?" model's final specification. Male and disabled respondents whose households sold more vehicles in the past 10 years, have more workers, and live farther from transit stops in highly populous neighborhoods (with everything else held constant) are more likely to purchase two vehicles. However, single respondents who travel more and live in poorer neighborhoods are inclined to buy only one vehicle.

Table 3.9: Bought two vehicles? (binary logit model results)

Covariates	**Coef.**	**T-stat**
Constant	-3.019	-6.74
Number of vehicles sold in the past 10 years	0.412	2.07
Distance to transit stop (from home) is greater than 3 miles?	0.527	1.67
Distance to downtown (from home) is greater than 5 miles?	-0.324	-1.01
Annual vehicle-miles traveled over 9,000 miles?	-0.552	-1.88
Disabled?	0.670	1.68
Number of workers in the household	0.335	1.87
Male?	0.460	1.63
Population density (per square mile)	2.62E-05	3.91
% of families below poverty line in the census tract	-0.021	-1.54
Single?	-0.744	-2.15
Fit statistics		
Null log-likelihood	-279.24	
Final log-likelihood	-257.68	
McFadden's R-square	0.077	
Adjusted R-square	0.074	
Number of observations	1033	

Table 3.10 shows the "bought new vehicle?" model's final specification. Older, licensed drivers, full-time workers, and male respondents whose households own more vehicles, have higher income, and live in neighborhoods with a higher density of employed individuals (all other attributes held constant) are more inclined towards buying new vehicles. In contrast, disabled respondents who have more workers in the household, sold at least one vehicle in the past 10 years, and live in highly populous neighborhoods are more likely to buy used vehicles.

The respondent's age, number of vehicles owned by the household, number of vehicles sold in the past 10 years, indicator for owning at least one vehicle, indicator for selling at least one vehicle in the past 10 years, and age of the oldest vehicle in the household are annually updated in the simulation.

Table 3.10: Bought new vehicle? (binary logit model results)

Covariates	Coef.	T-stat
Constant	-2.584	-3.53
Number of vehicles owned by the household	0.418	2.17
At least one vehicle in the household?	2.304	4.32
Age of the oldest vehicle in the household (in years)	-0.093	-4.39
Number of vehicles sold in the past 10 years	0.535	2.01
At least one vehicle sold in the past 10 years?	-2.162	-5.12
Disabled?	-0.639	-1.51
Number of workers in the household	-0.462	-2.98
Age (years)	0.011	1.41
Male?	0.349	1.44
Have U.S. driver license?	0.774	1.25
Household income	1.45E-05	4.25
Full-time worker?	0.708	2.73
Population density (per square mile)	-3.41E-05	-1.35
Employed and over 16 years of age (per square mile)	4.41E-05	1.29
Fit statistics		
Null log-likelihood	-467.04	
Final log-likelihood	-340.71	
McFadden's R-square	0.270	
Adjusted R-square	0.262	
Number of observations	721	

3.5.3 Forecasted Adoption Rates of CAV Technologies under WTP, Pricing, and Regulation Scenarios

Description of Scenarios

This simulation forecasts the annual adoption rates[11] of CAV technologies over the next 30 years (2016 to 2045) under eight different scenarios based on WTP, technology price, and NHTSA regulations (see Table 3.11).

As indicated in Tables 3.12 and 3.13, many respondents do not want to pay anything to add CAV technologies. For example, more than 50% of respondents have \$0 WTP to add Level 3 and Level 4 automation. Perhaps these respondents are not able to conceive a world with only CAVs and also may have various safety and reliability concerns about the technology. As the public learns more about CAVs and more people gain familiarity with these technologies, these perceptions and potential behavioral responses are apt to change, in some cases rapidly. In Scenario 1, the original WTP (as reported by the respondents) was considered and assumed constant over time. However, for all other scenarios (2 to 8), respondents who reported \$0 WTP were assigned a non-zero WTP[12] for year 2015, and their assigned WTPs (the 10th percentile value of all non-

[11] *Technology adoption rate* refers to the percentage of vehicles (population-weighted) having a specific technology. Vehicles with Level 3 and Level 4 automation are assumed to have all Level 1 and Level 2 automation technologies.

[12] To assign WTP to the respondents who do not want to pay anything for a specific technology, the sample was classified into 40 categories (based on household size, number of workers, and household vehicle ownership).

zero-WTP respondents in their demographic cohort) rose over time, at the same rate as everyone else's WTP.

Scenarios 1 and 2 do not consider any NHTSA current and probable technology adoption regulations, but the remaining scenarios (3 to 8) assume mandatory adoption of ESC from year 2015[13] and connectivity from year 2020[14] on all new vehicles.

Table 3.11: WTP increase, tech-pricing reduction, and regulation scenarios

Scenario	Annual WTP increment rate	Annual Tech-price Reduction Rate	Regulations
1	0%	10%	No
2	0%, but no zero WTP values	10%	No
3	0%, but no zero WTP values	5%	Yes
4	0%, but no zero WTP values	10%	Yes
5	5%	5%	Yes
6	5%	10%	Yes
7	10%	5%	Yes
8	10%	10%	Yes

As mentioned earlier, it is difficult to estimate the price of a particular Level 1 or Level 2 technology since automobile companies provide these technologies in packages. Thus, current prices for these technologies are approximately estimated by analyzing packages provided by BMW, Mercedes, and other manufacturers. Prices to add connectivity, Level 3, and Level 4 automation were estimated based on experts' opinions. Table 3.12 shows an example of temporal variation of the prices to add CAV technologies to the new vehicles[15] at the assumed annual price reduction rate of 5%.

Subsequently, a household that does not want to pay anything for specific technology was assigned a WTP of the 10th percentile of all non-zero WTP values in the household's category.

[13] ESC has been mandated on all new passenger vehicles in the U.S. since the 2012 model year (NHTSA 2012).

[14] NHTSA is expected to require connectivity on all vehicles produced after year 2020 (Automotive Digest 2014).

[15] In this study, costs for retrofitting a self-parking valet system, Level 1, and Level 2 automations into the used vehicles are assumed to be four times the cost of adding these technologies to new vehicles. For example, as per Table 312, the cost to add traffic sign recognition to the new vehicle is $450, but the cost for retrofitting it into a used vehicle is assumed to be $1800.

Table 3.12: Technology prices at 5% annual price reduction rates

Technology	2015	2020	2025	2030	2035	2040	2045
Electronic Stability Control	100	77.4	59.9	46.3	35.8	27.7	21.5
Lane Centering	950	735.1	568.8	440.1	340.6	263.5	203.9
Left-turn assist	450	348.2	269.4	208.5	161.3	124.8	96.6
Cross Traffic Sensor	550	425.6	329.3	254.8	197.2	152.6	118.1
Adaptive Headlights	1,000	773.8	598.7	463.3	358.5	277.4	214.6
Pedestrian Detection	450	348.2	269.4	208.5	161.3	124.8	96.6
Adaptive Cruise Control	400	309.5	239.5	185.3	143.4	111.0	85.9
Blind-spot Monitoring	400	309.5	239.5	185.3	143.4	111.0	85.9
Traffic Sign Recognition	450	348.2	269.4	208.5	161.3	124.8	96.6
Emergency Automatic Braking	450	348.2	269.4	208.5	161.3	124.8	96.6
Connectivity	200	154.8	119.7	92.7	71.7	55.5	42.9
Self-parking Valet	2,000	1,547.6	1,197.5	926.6	717.0	554.8	429.3
Level 3 Automation	15,000	11,606.7	8,981.1	6,949.4	5,377.3	4,160.8	3,219.6
Level 4 Automation	40,000	30,951.2	23,949.5	18,531.6	14,339.4	11,095.6	8,585.6

3.5.4 Overall Comparison of Technology Adoption in Eight Scenarios

Tables 3.13 to 3.16 present the estimated/simulated ownership rates (across all privately held light-duty vehicles, not just new vehicles being sold) at 5-year intervals, across the eight scenarios. Substantial differences are visible between the long-term adoption rates of all technologies (except Level 3 and Level 4 automation)[16] in Scenarios 1 (constant WTP) and 2 (constant WTP, but no zero WTP values[17]). For example, in 2045, connectivity's adoption rate is 59.5% in Scenario 1 and 83.5% in Scenario 2. Such differences emerged because a large proportion of households cannot adopt some technologies in Scenario 1, even at very low prices due to their WTP of $0.

The regulations' (regarding adoption of ESC and connectivity) effect on CAV technologies' adoption rates can be observed by comparing the results of Scenario 2 (see Table 2.15) and Scenario 4 (see Table 3.13), since WTP and technologies prices have the same dynamics in both scenarios. In Scenario 2 (no regulations), ESC and connectivity have adoption rates of 43.8% and 35.2% in 2025, but these numbers increase to 98.4% and 88.4%, respectively, due to incorporation of regulations in Scenario 4.

The technology-pricing impacts on the adoption of CAV technologies can be visualized by comparing adoption rates in Scenarios 3 and 4 (or 5 and 6, or 7 and 8), since these scenarios include regulations and have the same temporal variations in WTP, but different tech-price variations. Table 3.14 shows that most of the technologies' long-term adoption rates under an annual 10% tech-price reduction (Scenario 4) are much higher[18] than those under a 5% price- reduction

[16] In Scenario 2, all respondents with $0 WTP are assigned non-zero WTP values, but new WTP values are not enough to make advanced automation technologies affordable, even at 10% price drop rates. Thus, Level 3 and Level 4 automation adoption rates differ very little between Scenarios 1 and 2.

[17] No-zero WTP implies that there is no household in the sample with $0 WTP for any technology, since the sample has been corrected for this bias, as discussed above.

[18] However, for a few technologies, adoption rates are lower in Scenario 4 as compared to Scenario 3 at some point in time. For example, ESC's adoption rates (in 2025) are 98.6% in Scenario 3 and 98.4% in Scenario 4. These minor unintuitive differences might have occurred due to the noise of the simulation involving random number generation.

(Scenario 3), since technologies are obviously affordable for many more households in Scenario 4 as compared to Scenario 3. For example, in 2045, Level 4 automation's adoption rates are 24.8% in Scenario 3 and 43.4% in Scenario 4.

The effect of WTP increments on CAV technologies' adoption rates can be observed by comparing the results of Scenarios 4, 6, and 8 (or 3, 5, and 7), since these scenarios incorporate NHTSA regulations, and the same temporal variations of technology pricing, but different WTP variations. As expected, Tables 3.14, 3.15, and 3.16 demonstrate that, for most of the technologies, the long-term adoption rates in 0%, 5%, and 10% WTP increment scenarios show corresponding increases. For example, in 2045, Level 4 automation's adoption rates in Scenarios 4, 6, and 8 are 43.4%, 70.7%, and 87.2%, respectively.

Figure 3.5 graphs the estimated shares of U.S. light-duty vehicles with advanced automation for all eight levels.

Table 3.13: Estimated shares of U.S. light-duty vehicles with CAV-related technologies in scenarios 1 and 2

Technology	**Scenario 1:** *Constant WTP, 10% drop in tech-prices, and no regulation*							**Scenario 2:** *No-zero-WTP, 10% tech-price drop, and no regulation*						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electronic Stability Control	24.3	25.3	33.2	43.3	52.7	58.2	63.8	24.3	32.3	43.8	61.2	76.7	83.2	92.9
Lane Centering	4.4	8.3	18.9	31.0	40.8	48.8	56.8	4.4	8.6	20.2	33.5	45.9	55.2	68.8
Left-turn assist	3.8	9.9	20.1	32.4	41.8	50.3	58.1	3.8	10.4	21.8	35.1	47.2	65.6	80.2
Cross Traffic Sensor	10.9	12.9	22.6	35.1	45.1	52.6	60.3	10.9	13.8	25.9	41.1	53.7	66.0	82.8
Adaptive Headlights	10.2	9.7	18.8	30.9	41.0	49.2	58.0	10.2	9.8	19.8	32.4	46.2	55.9	77.5
Pedestrian Detection	3.7	10.6	21.7	34.5	44.1	52.6	59.8	3.7	11.2	24.1	38.2	50.3	69.1	82.8
Adaptive Cruise Control	13.3	14.9	24.1	35.2	44.7	52.2	59.8	13.3	16.2	27.0	40.1	53.4	62.2	76.1
Blind-spot Monitoring	11.7	15.0	26.1	38.5	48.2	55.1	62.1	11.7	17.3	31.9	46.3	59.7	67.8	80.7
Traffic Sign Recognition	2.0	7.7	18.0	30.0	39.8	48.9	57.0	2.0	7.6	18.4	31.4	43.5	63.3	78.6
Emergency Automatic Braking	5.6	11.8	24.4	37.1	46.9	54.6	61.6	5.6	11.8	26.4	43.7	57.7	74.3	86.2
Connectivity	0	17.7	34.8	44.7	51.1	53.0	59.5	0	18.0	35.2	46.1	57.6	61.4	83.5
Self-parking Valet	0	9.1	21.4	33.9	45.1	52.5	61.2	0	9.2	21.6	34.5	46.3	54.4	73.5
Level 3 Automation	0	2.1	4.6	7.6	8.3	8.0	10.4	0	3.0	5.3	7.7	8.7	7.9	13.7
Level 4 Automation	0	3.9	11.1	19.7	28.6	37.0	43.0	0	3.0	10.2	19.0	28.7	37.9	43.8

Table 3.14: Estimated shares of U.S. light-duty vehicles with CAV-related technologies in scenarios 3 and 4

Technology	**Scenario 3:** *No-zero-WTP, 5% drop in tech-prices, and regulations*							**Scenario 4:** *No-zero-WTP, 10% drop in tech-prices, and regulations*						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electronic Stability Control	24.3	88.9	98.6	99.8	100	100	100	24.3	89.1	98.4	99.9	100	100	100
Lane Centering	4.4	6.1	12.0	19.7	27.1	33.1	40.7	4.4	8.5	19.9	33.0	45.5	53.9	66.5
Left-turn assist	3.8	7.9	14.2	21.3	28.1	35.1	42.5	3.8	10.0	21.8	35.0	46.5	60.6	75.1
Cross Traffic Sensor	10.9	11.7	16.8	22.9	31.9	39.1	47.4	10.9	13.7	25.4	39.8	52.2	62.2	76.8
Adaptive Headlights	10.2	7.6	11.2	18.3	26.4	32.6	39.9	10.2	9.5	19.6	32.3	46.1	53.6	71.6
Pedestrian Detection	3.7	8.3	15.0	23.2	30.7	38.3	45.5	3.7	10.7	24.0	37.5	49.7	63.4	77.1
Adaptive Cruise Control	13.3	13.2	18.4	25.7	33.2	39.2	46.5	13.3	16.5	28.1	39.7	53.0	60.4	73.4
Blind-spot Monitoring	11.7	13.8	20.3	29.7	39.6	45.7	53.5	11.7	16.5	31.6	45.6	59.1	66.0	77.2
Traffic Sign Recognition	2.0	5.4	10.5	17.7	24.9	31.4	38.1	2.0	7.3	18.2	30.9	42.7	58.7	73.9
Emergency Automatic Braking	5.6	8.6	15.6	26.1	34.7	43.4	51.2	5.6	12.3	26.3	42.3	57.2	69.1	80.9
Connectivity	0	36.5	88.2	98.4	99.7	100	100	0	41.3	88.4	98.4	99.7	100	100
Self-parking Valet	0	6.0	13.1	20.9	29.0	34.9	41.6	0	9.2	21.1	33.4	45.7	53.4	71.9
Level 3 Automation	0	1.9	3.2	4.5	6.5	8.1	8.9	0	2.7	5.1	7.5	8.7	8.2	13.9
Level 4 Automation	0	2.0	5.2	10.3	15.0	19.2	24.8	0	2.9	10.2	18.8	28.5	36.3	43.4

Table 3.15: Estimated shares of U.S. light-duty vehicles with CAV-related technologies in scenarios 5 and 6

Technology	**Scenario 5:** *5% rise in WTP, 5% drop in tech-price, and regulations*							**Scenario 6:** *5% rise in WTP, 10% drop in tech-price, and regulations*						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electronic Stability Control	24.3	89.1	98.3	99.9	100	100	100	24.3	88.7	98.2	99.9	100	100	100
Lane Centering	4.4	8.5	21.1	33.5	43.5	53.1	59.8	4.4	10.3	26.8	44.5	56.5	81.4	92.9
Left-turn assist	3.8	10.3	22.0	35.0	44.4	59.2	71.5	3.8	11.9	27.8	44.8	66.2	88.1	96.3
Cross Traffic Sensor	10.9	14.3	25.7	39.6	50.6	60.9	73.4	10.9	15.7	32.1	50.2	68.9	87.3	96.3
Adaptive Headlights	10.2	10.0	20.5	32.3	43.4	53.0	67.1	10.2	11.0	26.4	44.5	63.4	84.8	95.4
Pedestrian Detection	3.7	11.1	24.5	38.1	47.9	61.4	74.0	3.7	13.2	30.9	48.5	68.6	88.6	96.5
Adaptive Cruise Control	13.3	16.1	27.4	39.4	51.8	60.3	68.3	13.3	18.3	33.9	51.5	66.7	86.4	95.8
Blind-spot Monitoring	11.7	17.5	30.8	44.6	57.5	66.3	73.6	11.7	17.8	37.7	57.3	71.6	88.4	96.3
Traffic Sign Recognition	2.0	7.1	19.0	30.7	41.4	56.5	70.0	2.0	8.6	24.5	41.0	63.8	87.3	96.2
Emergency Automatic Braking	5.6	11.6	26.4	42.4	54.6	67.3	77.8	5.6	14.1	34.2	55.0	73.3	91.0	97.2
Connectivity	0	39.1	89.3	98.5	99.8	100	100	0	40.5	88.8	98.2	99.7	100	100
Self-parking Valet	0	8.6	21.8	34.0	44.4	52.4	67.1	0	10.2	26.9	44.2	64.5	85.6	96.5
Level 3 Automation	0	2.3	5.3	8.1	8.5	8.3	8.2	0	2.1	6.1	8.4	8.5	28.6	16.3
Level 4 Automation	0	3.3	10.8	19.0	27.2	35.9	43.2	0	4.7	15.1	27.2	38.3	45.7	70.7

Table 3.16: Estimated shares of U.S. light-duty vehicles with CAV-related technologies in scenarios 7 and 8

Technology	**Scenario 7:** *10% rise in WTP, 5% drop in tech-price, and regulations*							**Scenario 8:** *10% rise in WTP, 10% drop in tech-price, and regulations*						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electronic Stability Control	24.3	89.7	98.1	99.8	100	100	100	24.3	89.1	98.8	99.9	100	100	100
Lane Centering	4.4	10.8	25.5	42.1	55.1	78.1	90.3	4.4	13.5	32.8	51.2	79.0	94.0	97.9
Left-turn assist	3.8	11.6	26.5	43.0	65.1	83.6	95.0	3.8	14.1	34.1	60.9	87.3	96.4	98.4
Cross Traffic Sensor	10.9	15.6	30.8	48.3	65.4	84.6	95.0	10.9	18.2	39.3	63.6	87.0	96.6	98.5
Adaptive Headlights	10.2	11.4	25.0	42.3	58.5	81.3	92.5	10.2	13.4	32.8	55.8	81.4	95.5	98.2
Pedestrian Detection	3.7	12.9	28.8	45.8	67.9	84.6	95.3	3.7	15.3	37.6	63.7	87.9	96.8	98.7
Adaptive Cruise Control	13.3	18.0	31.7	49.1	62.5	82.8	92.8	13.3	20.3	40.4	60.2	83.2	95.4	98.2
Blind-spot Monitoring	11.7	18.5	35.6	54.6	67.7	85.4	94.0	11.7	20.5	45.5	66.4	85.9	96.3	98.6
Traffic Sign Recognition	2.0	9.0	23.2	39.0	62.0	82.6	94.9	2.0	10.9	30.0	57.9	86.4	96.4	98.4
Emergency Automatic Braking	5.6	13.9	32.9	52.1	72.4	88.0	96.4	5.6	16.6	41.5	68.4	90.0	97.3	98.9
Connectivity	0	41.8	89.1	98.3	99.7	100	100	0	41.3	89.4	99.0	99.9	100.0	100.0
Self-parking Valet	0	10.5	25.5	41.6	57.6	82.4	92.9	0	12.6	32.9	54.6	80.3	96.0	99.4
Level 3 Automation	0	2.5	5.9	8.3	8.2	26.5	25.5	0	3.5	6.0	7.7	27.7	11.6	2.9
Level 4 Automation	0	4.7	13.8	25.5	36.4	44.3	59.7	0	5.5	19.4	33.8	44.2	74.7	87.2

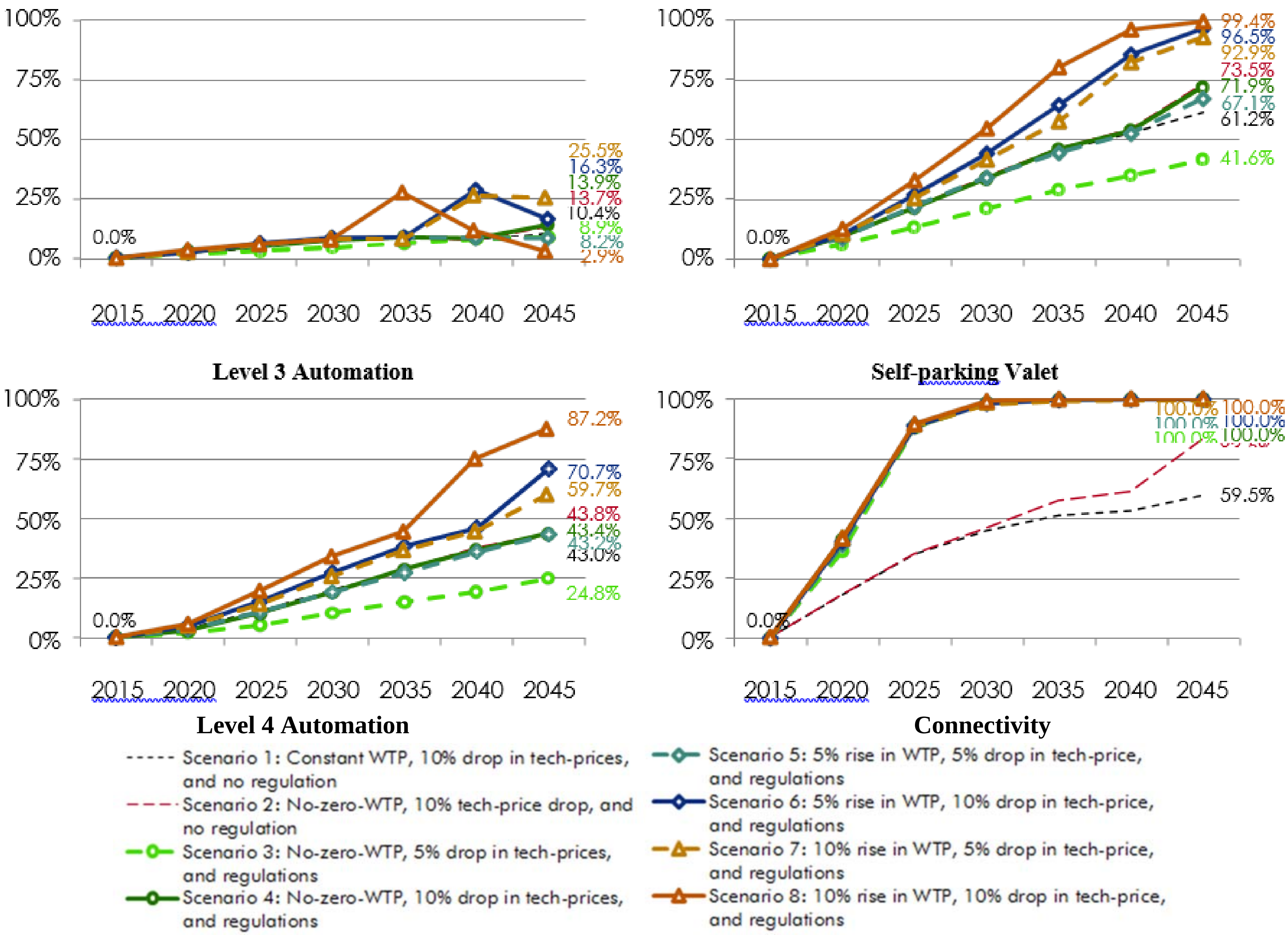

Figure 3.5: Estimated shares of U.S. light-duty vehicles with advanced automation

Adoption Rates of Connectivity, Level 1 and Level 2 Technologies

It is interesting to note that around 98% of the vehicle fleet is likely to have ESC and connectivity in years 2025 and 2030, respectively, under NHTSA's current and probable regulations (Scenarios 3 to 8). However, it is worth noting that in case of no regulations, even at a 10% annual drop in tech prices and no zero WTP values (Scenario 2), 92.9% of vehicles would have ESC and 83.5% would have connectivity in 2045 (see Table 3.13). NHTSA's regulations are likely to accelerate adoption of these technologies by 15 to 20 years, and make U.S. roads safer.

In Scenario 6 (5% rise in WTP and 10% drop in technology prices each year), Scenario 7 (10% rise in WTP and 5% drop in tech-prices), and Scenario 8 (10% rise in WTP and 10% drop in technology prices annually), all Level 1 technologies are estimated to have more than 90% adoption rates in 2045. Adoption rates of Level 1 technologies are further explored in Scenario 3 (5% drop in tech-prices and no zero WTP values) and Scenario 5 (5% rise in WTP and 5% drop in tech-prices). TSR is the least adopted and least appealing Level 1 technology in 2015, and is anticipated to remain least adopted, with adoption rates of 38.1% in 2045 in Scenario 3, but fourth-least adopted (out of nine, excluding ESC), with adoption rates of 70% in Scenario 5.[19] Section 3.4.3 suggests that blind-spot monitoring and emergency automatic braking are the two most appealing Level 1 technologies for Americans; these are anticipated to be the most and second-most adopted Level 1 technologies (excluding ESC) in 2045 in Scenario 3, with adoption rates of 53.5% and 51.2%; however, these are the third-most and most adopted Level 1 technologies in Scenario 5, with adoption rates of 73.6% and 77.8%. Pedestrian detection is the second-least adopted technology in 2015, but is expected to be the second-most adopted Level 1 technology (out of nine, excluding ESC) in 2045 in Scenario 5, with an adoption rate of 74.0%.

Adoption Rates of Advanced Automation Technologies

It is interesting to note that as WTP increases and tech prices drop, Level 4 automations' adoption rates shoot up while, at the same time, Level 3 automations' adoption rates decrease. For example, in 2045, Level 3 and Level 4 adoption rates are forecasted to be 8.2% and 43.2% in Scenario 5 (5% drop in tech-prices and 5% WTP rise), which change to 2.9% and 87.2% in Scenario 8 (10% drop in tech-prices and 10% WTP rise). This trend occurs because the simulation framework first checks whether a new-vehicle-buyer household can afford Level 4 automation (WTP exceeds the technology's price) in that specific year. If it can, then Level 4 automation is added to the new vehicle; otherwise, the same rule is checked for Level 3. So, with the increase in WTP or/and reduction in technology prices, many households will be able to afford Level 4 vehicles, so due to this hierarchical framework, Level 3 automation is automatically skipped from their choice sets. Self-parking valet system is likely to be adopted by 34.0% to 54.6% of the vehicle fleet in 2030 and 67.1% to 99.4% of the 2045 vehicle fleet.[20]

[19] Lane centering is the least adopted Level 1 technology in Scenario 5 in 2045, with an adoption rate of 59.8%.

[20] Lower bounds on adoption rates are anticipated for Scenario 5 (5% drop in tech-prices and 5% WTP rise) and upper bounds are forecasted for Scenario 8 (10% drop in tech-prices and 10% WTP rise).

3.6 Assessing Texans' Opinions about and WTP for Automation and CV Technologies

3.6.1 Survey Design and Data Acquisition and Processing

The team designed and disseminated another Texas-wide survey in June 2015 using Qualtrics, a web-based survey tool, following the same protocol outlined in Section 3.4.1 for the national survey.

Exploring respondents' opinions and preferences for the adoption of emerging vehicle and transport technologies, the survey asked 93 questions, divided into 7 sections. Respondents were asked about their opinions about AVs (e.g., concerns and benefits of AVs), crash history and opinions about speed regulations[21] (e.g., number of moving violations, and support for red light cameras and automated speed enforcement), WTP for and interest in various Level 1 and 2 technologies (e.g., adaptive headlights and ACC). Respondents were also asked about their WTP for and interest in CVs (e.g., road sign information using a head-up display), adoption rates of carsharing, ridesharing, and SAVs, their households' home-location shifting decisions (once AVs and SAVs become common modes of transport), opinions about congestion pricing strategies (e.g., toll if revenue is evenly distributed among residents), travel patterns (e.g., AVs' usage by trip purpose and distance from city's downtown), and demographics.

Data Cleaning and Sample Correction

A total of 1,297 Texans completed the survey, but after removing the fast responses and conducting some sanity checks[22], 1,088 responses remained eligible for further analysis. The sample over-represented specific demographic classes, such as men older than 65 years and bachelor's degree holders, and under-represented others, such as individuals who did not complete high school and men 18 to 24 years old. Therefore, the survey sample proportions in three demographic classes or sixty categories (two gender-based, five age-based, and six educational-attainment groups) were scaled using the 2013 American Community Survey's PUMS for Texas[23]. These scale factors were used as person-level weights to un-bias person- related summary statistics (e.g., concerns related to AVs) and model-based parameter estimate (e.g., binary opinion of whether or not to allow a 13 to 15-year-old children to ride alone in AVs). Similarly, some household groups were under- or over-represented. Thus, household weights were calculated for 3 demographic classes or 26 categories (4 household size groups, 4 household workers groups,

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[21] Respondents were asked about their crash history and opinions about speed law enforcement in order to explore the correlation of such attributes with their opinions of and WTP for CAV technologies.

[22] Respondents who completed the survey in less than 15 minutes were assumed to have not read questions thoroughly, and their responses were discarded. Respondents were provided with NHTSA's automation levels' definitions and, subsequently, were asked whether they understood this description or not. Those who did not understand it (5.7%, or 65 respondents) were considered ineligible for further analysis. Certain other respondents were also considered ineligible for further analysis: those younger than 18 years of age, reporting more workers or children than the household size, reporting the same distance of their home from various places (airport and city center, for example), and providing other combinations of conflicting answers

[23] Two categories—"Master's degree holder female and 18 to 24 years old" and "Master's degree holder male and 18 to 24 years old"—were missing in the sample data. These categories were merged with "Bachelor's degree holder female and 18 to 24 years old" and "Bachelor's degree holder male and 18 to 24 years old," respectively, in the population.

and 2 vehicle ownership groups)[24] using PUMS 2013 data. These household weights were used to un-bias household-related (e.g., WTP for new technologies and vehicle transaction decisions) model estimates and summary statistics.

3.6.2 Geocoding

To understand the spread of survey respondents across Texas and to account for the impact of built-environment factors (e.g., population density and population below poverty line) on respondents WTP for and opinions about CAV technologies, the respondents' home addresses were geocoded using Google Maps API and spatially joined with Texas's census-tract-level shape file using open-source Quantum GIS. For respondents who did not provide their street address or recorded incorrect addresses, their IP locations were used as the proxies for their home locations. Figure 3.6 shows the geocoded respondents across Texas, with most respondents living in or around Texas' biggest cities (Houston, Dallas, Fort Worth, San Antonio, and Austin), as expected in a relatively unbiased sample.

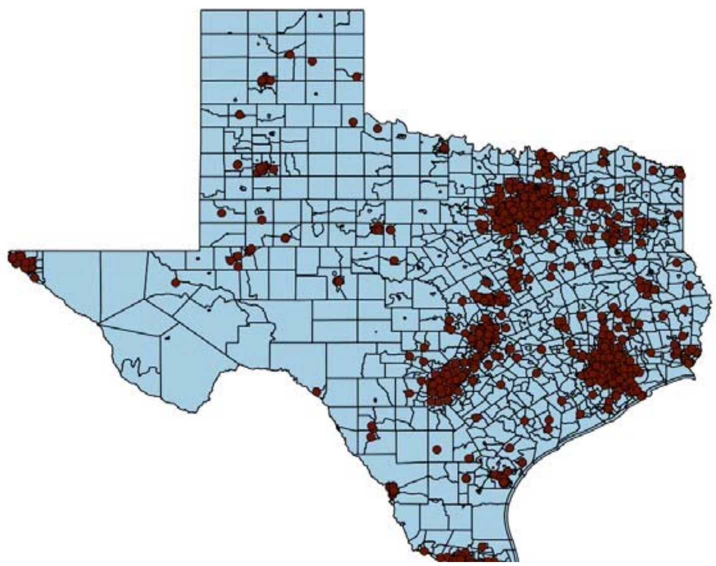

Figure 3.6: Geocoded respondents across Texas

3.6.3 Dataset Statistics

Table 3.17 summarizes all explanatory variables used in several model calibrations of this study. These are grouped into six categories, based on these predictors: person, household, location, travel, technology, and safety. Person- and household-based weights, as appropriate, were employed in calculating summary statistics and model calibration to correct for sample biases.

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[24] There are 32 combinations of traits (4 x 4 x 2 = 32), but there are only 26 categories used because some of the categories cannot exist. For example, the number of workers cannot exceed household size. A category "household with more than three members, more than two workers, and no vehicle" was missing and was merged with "household with more than three members, two workers, and no vehicle" in the population.

3.6.4 Texans' Technology-awareness and Safety-related Opinions

Technology-based predictors provide key insights about Texans' attitude towards new technologies. Around 77% of (population-weighted) Texans use a smartphone and a bit more than a half (59%) know about the existence of Google self-driving cars; however, only 19% have ever heard about CVs (before participating in the survey). Surprisingly, around two-thirds are familiar with on-demand ridesharing services like UberX and Lyft, but only 25% are aware about the carsharing programs. Only 7% of respondents' households own a modern vehicle with at least Level 2 automation.

Texans' attitudes towards safety-regulation strategies, crash history, and moving violation history are captured in the safety-based predictors. Around half of the respondents support each of these speed regulation strategies: red light cameras, automated speed enforcement, and speed governors. On average, Texans have experienced 0.25 crashes involving fatalities or serious injuries and 0.7 crashes involving monetary losses in past 15 years. Each respondent received at least one moving violation within past ten years, on average, while 20% received more than one violation. As per these statistics, Texans appear to be average drivers in terms of safety precautions.

Table 3.17: Population-weighted summary statistics of explanatory variables

Type	Explanatory Variable	Mean	SD	Min.	Max.
Person-based Predictors	Licensed driver (number of years)	19.11	12.50	0	32.5
	Licensed driver for more than 20 years	0.51	0.50	0	1
	Have U.S. driver license?	0.86	0.35	0	1
	Age of respondent (years)	44.56	16.31	21	69.5
	Younger than 34 years?	0.34	0.47	0	1
	Older than 54 years?	0.33	0.47	0	1
	Ethnicity: White, European white or Caucasian?	0.59	0.49	0	1
	Marital Status: Single?	0.33	0.47	0	1
	Marital Status: Married?	0.49	0.50	0	1
	Gender: Male?	0.49	0.50	0	1
	No disability?	0.90	0.09	0	1
	Bachelor's degree holder?	0.25	0.43	0	1
	Employment: Unemployed?	0.22	0.42	0	1
	Employment: Full-time worker?	0.34	0.47	0	1
Household-based Predictors	Household size over 3?	0.27	0.45	0	1
	Household income ($)	59,506	46,843	5,000	225,000
	Household income is less than $30,000?	0.28	0.45	0	1
	Household size	2.62	1.43	1	9
	Number of workers in household	1.21	0.89	0	6
	More than one worker in household?	0.36	0.48	0	1
	Own at least one vehicle?	0.94	0.24	0	1
	Number of children in household	0.62	1.05	0	6

Type	Explanatory Variable	Mean	SD	Min.	Max.
Location-based Predictors	Distance between home and public transit stop (miles)	6.12	6.20	0.5	17.5
	Distance between home and city's downtown (miles)	9.59	5.97	0.5	17.5
	Home and city's downtown are more than 10 miles apart?	0.47	0.50	0	1
	Distance from city center (miles)	9.85	7.46	0.5	25
	Employed and over 16 years of age (per square mile)	2,536	2,619	0	20,384
	% of families below poverty line in the census tract	13.01	11.20	0	100
	Population density (per square mile)	3,253	3,366	1	32,880
Travel-based Predictors	Drive alone for work trips?	0.51	0.50	0	1
	Number of personal business trips in past 7 days	1.58	2.26	0	9.5
	More than 2 personal business trips in past 7 days?	0.20	0.40	0	1
	Number of social (or recreational) trips in past 7 days	2.25	2.23	0	9.5
	More than 2 social (or recreational) trips in past 7 days?	0.31	0.46	0	1
	Annual VMT (miles)	8,607	6,391	1,500	22,500
	Annual VMT is more than 15,000 miles?	0.17	0.38	0	1
Tech-based Predictors	Carry a smartphone?	0.77	0.42	0	1
	Have heard about Google car?	0.59	0.49	0	1
	Familiar with UberX or Lyft?	0.64	0.48	0	1
	Have heard about CVs?	0.19	0.15	0	1
	Familiar with carsharing?	0.25	0.44	0	1
	Own at least a vehicle with Level 2 automation?	0.07	0.26	0	1
Safety-based Predictors	Support the use of Red Light Camera?	0.54	0.50	0	1
	Support the use of Automated Speed Enforcement?	0.52	0.50	0	1
	Support the use of Speed Governors on all new vehicles?	0.48	0.50	0	1
	Number of fatal (or serious) crashes in past 15 years	0.28	1.43	0	16
	At least one fatal (or serious) crash in past 15 years	0.08	0.27	0	1
	Number of crashes with only monetary loss in past 15 years	0.70	1.87	0	18
	Number of moving violations in past 10 years	0.97	2.23	0	26
	More than one moving violation in past 10 years?	0.20	0.40	0	1
Number of Observations = 1088					

3.6.5 Key Response Variables

Table 3.18 shows respondents' opinions about and average WTP for different automation levels and connectivity. Texans valued Level 2, Level 3, and Level 4 automations at $2,910, $4,607, and $7,589, on average; in contrast, 54.4%, 31.7%, and 26.6% of Texans are not willing to pay more than $1,500 for these technologies, respectively. As expected, the average WTP increases with level of automation. Interestingly, around half of Texans' (47%) will likely time their AV adoption in conjunction with their friends' adoption rates[25].

Texans are willing to spend $127, on average, for connectivity, but 29.3% of the respondents are not willing to spend a cent to add it, and only 39% are interested even if it is affordable. Thus, NHTSA's probable regulation on mandatory adoption of connectivity in all new vehicles from 2020 can play a key role in boosting CV adoption rates (Automotive Digest 2014).

Table 3.18: Population-weighted results of WTSP for and opinions about connectivity and automation technologies

Response Variable	Percentages	Mean	SD	Min.	Max.
WTP for Adding Connectivity		$127	$164	$0	$1,100
$0	29.3%				
$1 to $99	28.1%				
$100 to $199	20.4%				
$200 to $299	11.2%				
$300 or more	11.0%				
WTP for Adding LV 4 Automation		$7,589	$7,628	$750	$31,500
Less than $1,500	26.6%				
$1,500 to $5,999	28.7%				
$6,000 to $11,999	13.6%				
$12,000 or more	31.1%				
WTP for Adding LV 3 Automation		$4,607	$5,421	$750	$31,500
Less than $1,500	31.7%				
$1,500 to $2,999	24.5%				
$3,000 to $5,999	21.4%				
$6,000 or more	22.4%				
WTP for Adding LV2 Automation		$2,910	$4,312	$750	$31,500
Less than $1,500	54.4%				
$1,500 to $2,999	23.3%				
$3,000 or more	22.3%				
Adoption Timing of Level 4 AVs		**Response Variable**			**Percentages**
Never	39%	*Interest in adding connectivity*			
When 50% friends adopt	32%	Not interested			26%
When 10% friends adopt	15%	Neutral			35%
As soon as available	14%	Interested			39%

Number of Observations for Connectivity = 1063 **
Number of Observations for Automation of Technologies = 755 ***

***The questions about interest in and WTP for connectivity were only asked to the respondents (1,063 out of 1,088 respondents) who either have at least a vehicle or are planning to buy a vehicle in the next 5 years.*
**** The questions about WTP for different automation levels were only asked to the respondents (755 out of 1,088 respondents) who are planning to buy a vehicle in the next 5 years.*

[25] Another interesting opinion summary indicates that most Texans (80%) are not ready to send their children alone in self-driving vehicles and around the same proportion of respondents (78%) are not in support of banning conventional vehicles when 50% of all new vehicles are self-driving.

Table 3.19 shows respondents' opinions about SAV adoption in different pricing scenarios and home-location shifting decisions when AVs and SAVs become common modes of transport. Around 41% of Texans are not ready to use SAVs and only 7.3% hope to rely entirely on an SAV fleet, even at $1 per mile. AVs and SAVs are less likely to affect Texans' decisions about moving closer to or farther from the city center: about 81.5% indicated their intention to stay at their current locations. It is interesting that Texans' support for different congestion pricing policies do not vary much, on average. However, among three policies, most Texans (37.3%) support tolling congested highways if the resulting revenue can be used to lower property taxes.

Table 3.19: Population-weighted opinions about SAV adoption rates, congestion pricing, and home location shifting

Response Variable	**Percentages**	**Response Variable**	**Percentages**
Adoption Rates of SAVs at $1/mile		*Adoption Rates of SAVs at $2/mile*	
Will Not Use	41.0%	Will Not Use	48.6%
Less Than Once a Month	17.5%	Less Than Once a Month	19.8%
Once a Month	17.5%	Once a Month	15.4%
Once a Week	16.7%	Once a Week	11.6%
Rely Entirely	7.3%	Rely Entirely	4.6%
Adoption Rates of SAVs at $3/mile		*Home Location Shift due to AVs and SAVs*	
Will Not Use	59.1%	Move closer to city center	7.4%
Less Than Once a Month	17.2%	Stay at the same location	81.5%
Once a Month	11.7%	Move farther from city center	11.1%
Once a Week	8.1%		
Rely Entirely	3.9%		
Toll Congested Highways if Reduce Property Tax		*Toll Congested Highways if Distribute Revenues*	
Definitely not support	25.1%	Definitely not support	26.6%
Probably not support	11.5%	Probably not support	14.2%
Do not know	26.2%	Do not know	26.3%
Probably support	22.6%	Probably support	21.4%
Definitely support	14.7%	Definitely support	11.5%
Time-varying Tolls on All Congested Roadways			
Definitely not support	22.8%		
Probably not support	11.3%		
Do not know	31.8%		
Probably support	24.6%		
Definitely support	9.5%		
Number of Observations = 1088			

3.6.6 Opinions about AVs

Table 3.20 suggests that only 28.5% of Texans are not interested in owning or leasing Level 4 AVs (if affordable), indicating that they are excited about self-driving cars. Respondents were asked about the activities they believe they will perform while riding in a self-driving vehicle; talking to other passengers (59.5%) and looking out the window (59.4%) were two most popular responses[26]. Among those Texans who are interested in AVs, most would let their vehicle drive itself on freeways (60.9%) and in scenic areas (58.6%), but they are least comfortable riding in AVs on congested streets (36.1%). Among those who indicated interest in using self-driving vehicles, 33.9% are interested in using AVs for all trip types and 24.7% indicated interest in using AVs for social or recreational trips. Texans' average WTP to save 15 minutes of travel time on a 30-minute one-way trip is $6.80, but this figure increases to $9.50 if we remove those respondents with $0 WTP for this benefit (28.5%). This result indicates that most Texans associate significant monetary value with their travel time and are ready to pay more to travel faster. More than 30% of Texans are not ready to pay anything to ride in Level 4 AVs for all three trip types (i.e., work, shopping, and intercity). Consideration of riding with families or friends is not expected to improve WTP of respondents who do not want to pay anything, but for all three trip types, average WTP is the highest while riding in AVs with families (e.g., $7.30 for work trip) and lowest while riding alone (e.g., $6.10 for work trip)[27]. Average WTP to ride in Level 4 AVs on a one-way trip, among those with positive WTP, is the highest for the intercity trips ($18.10), and it increases to $20.40 for a ride with family. However, on a per-mile scale (i.e., considering average trip length of each trip type), the average WTP to ride in AVs is the highest for the shopping trips: $1.06 per mile for traveling alone and $1.26 for traveling with family.

[26] Around 45% of Texans eat or drink at least one a week while driving, but this proportion is expected to increase to 56% while riding in self-driving vehicles.
[27] However, average WTP to ride in Level 4 AVs is the same for riding alone or with the friends for work trips.

Table 3.20: Population-weighted opinions about Level 4 self-driving technology

Response Variable	Percentage	Response Variable	Percentage
Interest in Level 4 AVs (if affordable)			
Not Interested	28.5%	Moderately Interested	28.6%
Slightly Interested	21.0%	Very Interested	21.9%
Activities to be Performed while Riding in Level 4 AVs			
Watch movies or play games	27.3%	Sleep	18.1%
Surf the internet	33.3%	Look out the window	59.4%
Text, or talk on phone	46.2%	Exercise	7.8%
Talk to others in a car	59.5%	Maintenance activities	17.5%
Eat or drink	56.0%	Work	17.4%
Read	24.5%		
Like to Ride in AVs on (Nobs = 863)[28]			
Freeway	60.9%	Scenic Areas	58.6%
Less congested streets	51.0%	Parking	43.6%
Congested streets	36.1%	Other	8.1%
Set Self-drive Mode During (Nobs = 863)			
All types of trips	33.9%	Personal business trip	17.0%
Work trip	17.0%	Social or recreational trip	24.7%
School trip	7.0%	Shopping trip	17.9%
WTP to Save 15 Minutes of Travel Time on One-way Trip			
Will not pay anything	28.5%	Will pay more than $0	71.5%
WTP to Ride in AVs on One-way Journey	**Ride alone**	**Ride with family**	**Ride with friends**
Will not pay anything (%)			
Work trip	41.2%	43.1%	42.7%
Shopping trip	38.6%	37.9%	39.6%
Next closest big city	30.1%	29.9%	31.6%
WTP, for All Respondents ($)			
Work trip	$5.9	$7.7	$5.9
Shopping trip	$6.1	$7.3	$6.9
Next closest big city	$12.7	$14.3	$13.4
WTP, for Those with WTP > 0 ($)			
Work trip	$10.1	$13.6	$10.3
Shopping trip	$9.9	$11.8	$11.5
Next closest big city	$18.1	$20.4	$19.6
Typical One-way Distance (miles)			
Work trip	11.29		
Shopping trip	9.38		
Next closest big city	53.11		
Number of Observations = 1088			

[28] The respondents who intend to never ride in AVs were not asked about their AV usage preferences based on trip type or road characteristics.

Table 3.21 summarizes key concerns and benefits of AVs. Affordability and equipment failure are the top two concerns regarding AVs; the two least concerning aspects are learning how to use AVs and, surprisingly, privacy breaches. Texans expect that AVs can help attain better fuel economy and also reduce crashes: 53.9% and 53.1% of the respondents, respectively, indicated that these benefits will be very significant.

Table 3.21: Major concerns and benefits associated with AVs

Major Concerns Associated with Self Driving	**Not Worried**	**Slightly Worried**	**Very Worried**
Equipment failure	8.4%	30.2%	61.4%
Legal liability	14.2%	32.8%	52.9%
Hacking of vehicle	15.1%	29.9%	55.1%
Privacy breach	26.3%	39.0%	34.7%
Interactions with conventional vehicles	11.7%	34.5%	53.8%
Learning to use AVs	37.6%	37.7%	24.7%
Affordability	9.1%	26.4%	64.5%
Major Benefits from AVs	**Insignificant**	**Slightly Significant**	**Very Significant**
Fewer crashes	7.3%	39.6%	53.1%
Less congestion	10.8%	44.6%	44.6%
Lower emissions	11.7%	42.5%	45.7%
Better fuel economy	7.7%	38.4%	53.9%
Number of Observations = 1088			

3.6.7 Opinions about CVs

Table 3.22 demonstrates Texans' current usage and interest in certain connectivity features. Automated notification of emergency services in an event of an accident and vehicle health reporting are the two most interesting connectivity features for Texans; 71.5% and 68.5% of respondents are interested in these features. In-vehicle features allowing one to compose emails and surfing internet via in-built car displays are the two least interesting features; 58.1% and 51.5% of the respondents indicated no interest in these features. However, most of the features have less than 10% adoption rates. Real-time traffic information and operating a smartphone using controls on a steering wheel are the two most adopted features, with current adoption rates of 15.6% and 13.4%.

Table 3.22: Current adoption and interest in connectivity features

	Not Interested	Interested	Already Using
Real-time traffic information	22.6%	61.8%	**15.6%**
Alert about the presence of roadside speed cameras	27.6%	65.6%	6.7%
Information about nearby available parking	33.6%	61.7%	4.7%
Automatic notification to emergency personnel in the event of an accident	18.8%	**71.5%**	9.7%
Automatic monitoring of driving habits by insurance companies	49.6%	44.2%	6.2%
Personal restrictions (example: certain speed limits for teenagers)	38.4%	53.8%	7.8%
Alcohol detection	38.0%	53.8%	8.2%
Road sign information	37.4%	58.1%	4.5%
Cabin pre-conditioning	27.3%	65.6%	7.1%
Vehicle health report	19.3%	**68.5%**	12.2%
Vehicle life-cycle management	23.2%	63.5%	13.3%
Surfing the Internet via a built-in car display	**51.5%**	43.2%	5.2%
In-vehicle feature allowing to use email	**58.1%**	38.3%	3.6%
Operating a smartphone using controls on the steering wheel	38.5%	48.1%	**13.4%**
Number of Observations = 1063			
The questions about interest in connectivity features were only asked to the respondents (1,063 out of 1,088 respondents) who either have at least a vehicle or are planning to buy a vehicle in the next 5 years.			

Table 3.23 suggests that Texans are most likely to support adaptive traffic signal timing and least likely to support real-time adjustment in parking prices (when 80% of vehicles are connected); 64.0% and 20.5% of respondents support these policies, respectively. On average, Texans rank safety as the most important and climate change as the least important area of improvement in automobile technologies.

Table 3.23: Support for CV-related strategies and improvements in automobile technologies

	Do Not Support	No Opinion	Support
Adaptive traffic signal timing to ease congestion	13.0%	23.1%	**64.0%**
Real-time adjustment of parking prices	48.5%	31.0%	**20.5%**
Variable toll rates on congested corridors	37.3%	29.2%	33.5%
Variable speed limits based on road and weather conditions	18.3%	19.5%	62.2%
Areas of Improvement	**Average Rank**		
Safety	1.36		
Emissions (excluding greenhouse gas)	2.27		
Travel times (and congestion)	2.64		
Energy use and climate change	2.67		
Number of Observations = 1088			

3.6.8 Opinions about Carsharing and Ridesharing

Table 3.24 shows that, among those who have heard about carsharing, only 10% are members of carsharing programs (e.g., Zipcar or Car2Go). The members indicated that environmental friendliness and monetary savings are the two key reasons behind joining these programs. Among non-member respondents, most (75.5%) find no reason to join a carsharing program because they rely on other means of transportation. Among those who have heard about UberX or Lyft, only 12.2% actually used it at least once as a passenger. According to UberX or Lyft users, monetary and time savings are the two key reasons for using these ridesharing services. Lastly, only 16.4% of Texans are comfortable in sharing a ride with a complete stranger.

Table 3.24: Opinions about carsharing and on-demand taxi services

Carsharing (Zipcar, Gar2Go)			
Heard about carsharing	25.5%		
Among those who have heard about carsharing:			
Member of Zipcar or Car2Go	9.9%	Not a member	90.1%
Why a member? (Among members)		**Why not a member? (Among non-members)**	
Saves money	68.2%	Not available where I live	25.9%
Saves time	60.0%	Inconvenient availability or location	21.6%
Environmentally friendly	68.7%	Own a vehicle, use transit, or walk	75.5%
Necessity (I have no car)	38.6%	It is expensive	10.3%
Good back up	35.9%	Not ready to share a vehicle	27.6%
Other	5.2%	Other	18.2%
On-demand Taxi Service (UberX or Lyft)			
Heard about UberX or Lyft	64.0%		
Among those who heard about UberX or Lyft:			
Used UberX as a Passenger	12.2%		
With Whom Will be Comfortable Sharing a Ride			
With a stranger	16.4%	With close friends and family	75.9%
With a friend of a friend	39.9%	Other	2.6%
With regular friends and family	45.4%		
Among those who Have Used UberX as Passengers			
Why Used UberX			
To save money	54.4%	No need to worry about parking	21.4%
To save time	47.0%	My vehicle was unavailable	16.9%
To try it out	43.3%	Promotion	24.1%
To avoid driving	41.6%	Other	4.0%
Number of Observations = 1088			

3.6.9 Model Estimation

This study estimated WTP to add connectivity and different levels of automation using an IR model.[29] Please see Wooldridge (2013) to explore details about the IR model, which is succinctly presented here for a response variable for only interval data.[30] The key equation is as follows:

[29] Respondents were asked to choose WTP interval (e.g., \$1,500 to \$2,999 to add automation) and also provided with options of “\$3,000 or more” and \$1,000 or more” in the questions about WTP to add automation and connectivity, respectively; the response variable is right-censored interval data type. IR is appropriate (a form of linear regression) here for modeling such data types, since it considers interval boundaries as fixed parameters, unlike an OP model.

[30] IR can be used to model point, interval, right-censored, and left-censored data types.

$$y_j = \beta' x_j + \varepsilon_i, \tag{1}$$

where subscript "j" denotes an individual observation ($j \in C$) and C is the set of all observations. It is already known that $y_j \in [y_{lj}, y_{rj}]$ (a known interval with lower bound y_{lj} and upper bound y_{rj}); x_i represents a vector of covariates for each individual; β represents a vector of regression coefficients, which are to be estimated; and ε_j is the error term, which is distributed normally with mean zero and standard deviation of σ. The log-likelihood can be written as follows:

$$\log L = \sum_{j \in C} w_j \log\left\{\varphi\left(\frac{y_{rj}-\beta' x_j}{\sigma}\right) - \varphi\left(\frac{y_{lj}-\beta' x_j}{\sigma}\right)\right\}, \tag{2}$$

where φ is the standard cumulative normal and w_j is a population-corrected weight for the j^{th} observation.

Additionally, interest in adding connectivity (if affordable), adoption timing of AVs, adoption rates of SAVs under three pricing scenarios ($1, $2, and $3 per mile), future home-location shifts (after AVs and SAVs become common modes of transport), and opinions about three congestion pricing policies were estimated using ordered probit (OP) specifications in Stata 12 software (Long and Freese 2006). The OP model specifications are presented here in the context of interest in CVs. The main equation for this specification is as follows (Greene 2012):

$$y_i^* = \beta' x_i + \varepsilon_i, \tag{3}$$

where subscript i denotes an individual observation; y_i^* represents the individual's latent inclination to add connectivity (if affordable); x_i represents a vector of covariates for each individual; β represents a vector of regression coefficients, which are to be estimated; and ε_i represents a random error term assumed to follow a standard normal distribution.

For this example, two thresholds (μ_1 through μ_2) were estimated to distinguish the three categories; where μ_1 represents the threshold between "not interested" and "neutral" and μ_2 is the threshold between "neutral" and "interested in adding connectivity at a cost of less than $100". Under this specification, the opinion probabilities are as follows:

$$\Pr(\text{not interested}) = \Pr(y_i^* \leq \mu_1), \tag{4}$$
$$\Pr(\text{neutral}) = \Pr(\mu_1 \leq y_i^* \leq \mu_2), \tag{5}$$
$$\Pr(\text{interested}) = \Pr(y_i^* \geq \mu_2). \tag{6}$$

Initial model specifications included a subset of Table 3.17's explanatory variables. The models were re-estimated using stepwise elimination by removing the covariates with the lowest statistical significance until all p-values were less than 0.32, which corresponds to a |Z-stat| of 1.0. Although most of the explanatory variables enjoy a p-value greater than .05 (|Z-stat| > 1.96), covariates with p-values lower than 0.32 (which corresponds to a |Z-stat| of greater than 1.0) were also kept in the final specification. McFadden's R-Square and adjusted R-square are calculated to measure the models' goodness of fit.

3.6.10 Interest in and WTP to Add Connectivity

Table 3.25 summarizes the OP and IR model estimates of Texans' interest in and WTP for adding connectivity to current and future vehicles. These results indicate that more experienced licensed drivers and single individuals are less interested in adding connectivity and have lower WTP for it. Men who are familiar with carsharing, support speed regulation strategies, carry smartphones, drive alone for work, make more social/recreational trips, live far away from downtown, and have higher household income (everything else held constant) are estimated to have more interest in adding connectivity (if it is affordable), but respondents living farther from transit stops are less interested.

Disabled men with bachelor degrees who are familiar with ridesharing services, travel more, make more business trips, support speed governors, and encountered more moving violations and more fatal crashes in the past (all other predictors held constant) have higher WTP for adding connectivity, but older Caucasians with more members in the household are estimated to place lower value on connectivity. Perhaps the educated, safety-seeking, and tech-savvy respondents are able to perceive the safety benefits of connectivity during their longer travels.

Table 3.25: Interest in connectivity (OP) and WTP for connectivity (IR) model results

Covariates (Model 1: Interest in Connectivity, if Affordable)	**Coef.**	**Z-stat**
Licensed driver (number of years)	-0.032	-4.98
Support the use of Automated Speed Enforcement?	0.483	3.7
Support the use of Speed Governors on all new vehicles?	0.555	4.12
Number of fatal (or serious) crashes in past 15 years	0.407	2.08
Carry smartphone?	0.541	3
Familiar with carsharing?	0.418	2.95
Drive alone for work trips?	0.25	1.91
More than 2 social (or recreational) trips in past 7 days	0.234	1.82
Distance between home and public transit stop (miles)	-0.02	-2.02
Home and city's downtown are more than 10 miles apart?	0.17	1.35
Male?	0.298	2.24
Household income ($)	2.36E-06	1.75
Single?	-0.351	-2.25
Thresholds	**Coef.**	**Std. Dev.**
Not interested **vs.** Neutral	-0.356	0.282
Neutral **vs.** Interested	1.368	0.285
Nobs: 1063 **McFadden's R-Square:** 0.082 **McFadden's adjusted R-Square:** 0.070		

Covariates (Model 2: WTP for Connectivity)	**Coef.**	**Z-stat**
Intercept	151.40	4.64
Number of moving violations in past 10 years	10.01	5.96
Support the use of Speed Governors on all new vehicles?	48.37	5.04
Number of fatal (or serious) crashes in past 15 years	6.69	1.95
Number of crashes with only monetary loss in past 15 years	3.79	1.45
Familiar with UberX or Lyft?	21.03	2.04
Licensed driver (number of years)	-2.48	-3.24
Number of personal business trips in past 7 days	4.48	2.27
Annual VMT (miles)	1.95E-03	2.44
No disability?	-17.89	-1.23
Household size	-7.20	-1.90
Age of Respondent (years)	-0.99	-1.74
Male?	10.32	1.11
White, European white or Caucasian?	-19.66	-1.98
Household income ($)	5.96E-04	7.16
Bachelor's degree holder	15.03	1.52
Single?	-17.22	-1.48
sigma	138.30	-
Nobs: 1063 **McFadden's R-Square:** 0.038 **McFadden's adjusted R-Square:** 0.034		

3.6.11 WTP for Automation Technologies

Table 3.26 summarizes the IR model specifications of WTP to add Level 2, 3, and 4 automations. As expected, intercepts in these models rise along with the increase in levels of automation. Respondents who have heard about the Google self-driving car (before taking the survey), support speed governors on all new vehicles, and have higher household income (everything else held constant) are estimated to pay more for all levels of automation. However, consistent with the findings of the *WTP for connectivity* model, older and more experienced licensed drivers are expected to place lower value on automation technologies. Perhaps older individuals are finding it difficult to conceive that CAVs are about to hit the roads and licensed drivers who particularly enjoy driving might be worried about sacrificing those elements of driving they find enjoyable. Individuals with higher annual VMT are willing to pay more for Level 4 automation, but that preference is inverted for those living in more densely populated neighborhoods. Those who live farther from transit stops are expected to pay less for Level 3 and Level 4 automation. Caucasians' WTP for Level 2 automation is estimated to be lower than for other ethnicities, as is the case for connectivity, implying that non-Caucasians are likely to be early adopters of CAV technologies. Interestingly, those who experienced more fatal crashes in the past are significantly interested in paying more for Level 2 and Level 3 automations (as is the case for connectivity); surprisingly, this relationship is reversed for those who are familiar with ridesharing services.

Table 3.26: WTP for automation technologies (IR model results)

Covariates (Model 1: WTP for Level 4 Automation)	Coef.	Z-stat
Intercept	10300	7.43
Have heard about Google car?	1521	2.64
Support the use of Speed Governors on all new vehicles?	1755	3.32
Have heard about CVs?	931.1	1.28
Licensed driver (number of years)	-61.07	-1.27
Distance between home and public transit stop (miles)	-75.18	-1.60
Annual VMT (miles)	9.96E-02	2.40
Age of Respondent (years)	-104.60	-2.71
Household income ($)	1.04E-02	1.81
Single?	1000	1.63
Population density (per square mile)	-0.11	-1.29
sigma	6961	-
Nobs: 755 **McFadden's R-Square:** 0.035 **McFadden's adjusted R-Square:** 0.029		
Covariates (Model 2: WTP for Level 3 Automation)	**Coef.**	**Z-stat**
Intercept	7179	7.17
Have heard about Google car?	1094	2.58
Support the use of Speed Governors on all new vehicles?	1229	3.27
Number of fatal (or serious) crashes in past 15 years	438.6	4.82
Familiar with UberX or Lyft?	-506.8	-1.21
Licensed driver (number of years)	-54.56	-1.52
Number of personal business trips in past 7 days	96.91	1.06
Distance between home and public transit stop (miles)	-42.49	-1.26
Distance between home and city's downtown (miles)	40.98	1.22
Age of Respondent (years)	-73.12	-2.45
Household income ($)	7.53E-03	1.79
sigma	4792	-
Nobs: 755 **McFadden's R-Square:** 0.044 **McFadden's adjusted R-Square:** 0.039		
Covariates (Model 3: WTP for Level 2 Automation)	**Coef.**	**Z-stat**
Intercept	5059	6.65
Have heard about Google car?	896.8	2.45
Support the use of Speed Governors on all new vehicles?	1241	3.94
Number of fatal (or serious) crashes in past 15 years	554.6	8.36
Familiar with UberX or Lyft?	-750.7	-2.24
Licensed driver (number of years)	-51.35	-1.80
Household size over 3?	-501.4	-1.57
Age of Respondent (years)	-38.91	-1.63
White, European white or Caucasian?	-467.8	-1.39
Household income ($)	5.55E-03	1.69
sigma	3743	-
Nobs: 755 **McFadden's R-Square:** 0.048 **McFadden's adjusted R-Square:** 0.042		

3.6.12 Adoption Timing of Autonomous Vehicles

Table 3.27 summarizes OP model estimates of AV adoption timings (i.e., never adopt AVs, adopt AVs when 50% of friends adopt, when 10 % of friends adopt, or as soon as available in the market). The adoption timing of disabled individuals and bachelor's degree holders who support speed-regulation strategies, are familiar with carsharing, travel more, have more than one worker in the household, and live in a neighborhood with a higher density of employed individuals—all other predictors held constant—are less likely to depend on friends' adoption rates. In contrast, the adoption timing of older, single, and Caucasian respondents who have larger households and live in more densely populated neighborhoods is estimated to be more dependent on friends' adoption rates. These estimates appear to be consistent with the *WTP for automation technologies* model specification,[31] i.e., the AV adoption timing of those who indicate higher WTP for AVs is less likely to depend on their friends' adoption rates.

Table 3.27: Adoption timing of AVs (OP model results)

Covariates	**Coef.**	**Z-stat**
Support the use of Automated Speed Enforcement?	0.455	1.82
Support the use of Speed Governors on all new vehicles?	0.365	1.99
Have heard about CVs?	0.362	1.52
Familiar with carsharing?	0.336	2.19
Distance between home and public transit stop (miles)	-0.051	-2.44
Annual VMT (miles)	3.13E-05	1.74
No disability?	-0.454	-1.65
Household size	-0.109	-1.69
More than 1 worker in household?	0.259	1.41
Age of Respondent (years)	-0.025	-2.53
White, European white or Caucasian?	-0.273	-1.32
Bachelor's degree holder	0.260	1.50
Single?	-0.385	-1.83
Population density (per square mile)	-1.76E-04	-1.47
Employed and over 16 years of age (per square mile)	1.96E-04	1.09
Thresholds	**Coef.**	**Std. Dev.**
Never **vs.** 50% friends adopt	-1.898	0.665
50% friends adopt **vs.** 10% friends adopt	-0.303	0.688
10% friends adopt **vs.** As soon as available	0.555	0.738
Nobs: 1,088 **McFadden's R-Square:** 0.059 **McFadden's adjusted R-Square:** 0.046		

3.6.13 SAV Adoptions Rates under Different Pricing Scenarios

Table 3.28 summarizes the OP model estimates of SAV adoption rates (i.e., relying on an SAV fleet less than once a month, at least once a month, at least once a week, or entirely) under different pricing scenarios ($1 per mile [Model 1], $2 per mile [Model 2], and $3 per mile [Model

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[31] As an exception, single respondents are estimated to have higher WTP to add Level 4 automation (other attributes held constant), but their adoption timing is more dependent on their friends' adoption rates.

3]). Respondents who experienced fatal crashes in the past, support speed regulation strategies, have heard about CVs, live farther from downtown, and have more workers in households, all other predictors held constant, are likely to use SAVs frequently. In contrast, consistent with *WTP for automation technologies* model findings, Caucasians who are licensed (or more experienced) drivers and live farther from transit stops are estimated to use SAVs less frequently in all three pricing scenarios.[32]

It is worth noting that even unemployed and lower income households (with annual household income less than $30,000) are estimated to use SAVs more frequently at $1 per mile; perhaps SAVs are affordable for these individuals at this price. Male respondents who travel more also expect to use SAVs more frequently at $1 per mile, since they can readily evaluate cost-reduction benefits at this lower price. Respondents who have experienced more moving violations in the past are expected to use SAVs frequently at $1 and $2 per mile; perhaps they can visualize that SAVs can save them from future violations[33]. Interestingly, married respondents who are familiar with UberX (everything else held constant) are estimated to use SAVs less frequently, but those who make more social/recreation trips are expected to use SAVs frequently at even $2 and $3 per mile (more than what carsharing companies and UberX charge). Perhaps those who know about ridesharing services are not willing to pay additional charges to enjoy SAVs' additional utilities (on top of traditional ridesharing); the vehicle ownership level (not controlled here) of married couples might be discouraging them from using SAVs at higher prices. Lastly, perhaps bigger households are likely to use SAVs as an alternative to a second vehicle and disabled individuals are able to perceive the maximum utility of SAVs, and thus both demographic groups are likely to use SAVs more frequently, even at $3 per mile.

[32] Since household vehicle ownership is not controlled here, the respondents showing negative inclination towards SAVs may have higher vehicle ownership, on average.

[33] However, even respondents who experienced more moving violations in the past do not attach statistical significance to the SAVs' utility of saving them from future violations at $3 per mile.

Table 3.28: SAV adoption rates under different pricing scenarios (OP model results)

Covariates (Model 1: $1 per mile)	**Coef.**	**Z-stat**
Number of moving violations in past 10 years	0.081	1.91
Support the use of Automated Speed Enforcement?	0.407	2.11
Support the use of Speed Governors on all new vehicles?	1.040	5.49
At least 1 fatal (or serious) crash in past 15 years?	0.615	1.64
Have heard about CVs?	0.501	1.64
Distance between home and public transit stop (miles)	-0.038	-2.15
Distance between home and city's downtown (miles)	0.025	1.66
Annual VMT more than 15,000 miles?	0.298	1.35
Number of workers in household	0.227	2.34
Male?	-0.257	-1.29
Have U.S. driver license?	-1.163	-3.15
White, European white or Caucasian?	-0.419	-2.13
Household income less than $30,000?	0.425	2.11
Unemployed?	0.508	2.10
Thresholds	**Coef.**	**Std. Dev.**
Will never use **vs.** Will rely less than once a month	-2.510	0.431
Will rely less than once a month **vs.** Will rely at least once a month	-0.769	0.412
Will rely at least once a month **vs.** Will rely at least once a week	0.510	0.411
Will rely at least once a week **vs.** Will rely entirely on SAV fleet	2.409	0.455
Nobs: 730 **McFadden's R-Square:** 0.113 **McFadden's adjusted R-Square:** 0.097		
Covariates (Model 2: $2 per mile)	**Coef.**	**Z-stat**
Licensed driver (number of years)	-0.017	-1.60
Number of moving violations in past 10 years	0.093	1.90
Support the use of Automated Speed Enforcement?	0.515	2.40
Support the use of Speed Governors on all new vehicles?	0.899	4.02
Number of fatal (or serious) crashes in past 15 years	0.179	1.62
Have heard about CVs?	0.640	2.47
Familiar with UberX or Lyft?	-0.527	-2.24
Drive alone for work trips?	-0.330	-1.61
More than 2 social (or recreational) trips in past 7 days	0.401	1.95
Distance between home and public transit stop (miles)	-0.057	-2.90
Distance between home and city's downtown (miles)	0.036	2.17
Number of workers in household	0.277	2.21
Older than 54 years?	-0.498	-2.05
White, European white or Caucasian?	-0.379	-1.92
Married?	-0.383	-1.98

Thresholds	Coef.	Std. Dev.
Will never use **vs.** Will rely less than once a month	-1.435	0.443
Will rely less than once a month **vs.** Will rely at least once a month	0.040	0.429
Will rely at least once a month **vs.** Will rely at least once a week	1.302	0.444
Will rely at least once a week **vs.** Will rely entirely on SAV fleet	3.191	0.536
Nobs: 730 **McFadden's R-Square:** 0.123 **McFadden's adjusted R-Square:** 0.108		
Covariates (Model 3: $3 per mile)	**Coef.**	**Z-stat**
Licensed driver (number of years)	-0.018	-2.28
Support the use of Automated Speed Enforcement?	0.475	2.37
Support the use of Speed Governors on all new vehicles?	0.895	4.34
Number of fatal (or serious) crashes in past 15 years	0.191	3.61
Have heard about CVs?	0.874	3.03
Familiar with UberX or Lyft?	-0.259	-1.38
Number of social (or recreational) trips in past 7 days	0.080	1.68
Distance between home and public transit stop (miles)	-0.056	-3.01
Distance between home and city's downtown (miles)	0.032	1.86
No disability?	-0.495	-1.72
Household size over 3?	0.291	1.49
Number of workers in household	0.127	1.17
White, European white or Caucasian?	-0.661	-3.40
Married?	-0.452	-2.33
Thresholds	**Coef.**	**Std. Dev.**
Will never use **vs.** Will rely less than once a month	-0.828	0.475
Will rely less than once a month **vs.** Will rely at least once a month	0.326	0.479
Will rely at least once a month **vs.** Will rely at least once a week	1.632	0.490
Will rely at least once a week **vs.** Will rely entirely on SAV fleet	3.381	0.606
Nobs: 730 **McFadden's R-Square:** 0.121 **McFadden's adjusted R-Square:** 0.105		
Note: The respondents were first asked about their SAV adoption rates if the SAV service were affordable. Those who never want to use SAVs (358 out of 1088 respondents), even if they are affordable, were not asked the questions about SAVs' adoption rates under different pricing scenarios.		

3.6.14 Home Location Shifts due to AVs and SAVs

Table 3.29 summarizes the OP model estimates of respondents' home-location-shift decisions (i.e., shift closer to central Austin, stay at the same location, or move farther from central Austin)[34] after AVs and SAVs become common modes of transport. Bachelor's degree holders,

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[34] This model alone can obtain inferences about two groups' characteristics: those "who want to shift closer to the city center or stay at the same location" and those "who want to shift farther from the city center or stay at the same location." However, to explore the characteristics of population groups "who want to shift closer to the city center" and "who want to shift farther from the city center," a new binary logit model was estimated so as to explore the individual characteristics of those "who want to stay at the same location" after AVs and SAVs become common modes of transport. For example, according to OP model estimates, those who are familiar with UberX are either

single individuals, and full-time workers who support speed governors, own at least a vehicle with Level 2 automation, have experienced more fatal crashes in past, and live farther from a city center—all other attributes held constant—are likely to shift closer to the city center. Perhaps these individuals are excited about higher density of low-cost SAVs near city center. However, respondents who live farther from transit stops, make more social/recreation trips, and are familiar with UberX (everything else held constant) are predicted to shift farther from the city center. Perhaps these individuals are concerned about higher land prices in the urban neighborhoods, and are keen to enjoy the benefits of moving to suburban areas after AVs and SAVs become common modes of transport.

Table 3.29: Home location shifts due to AVs and SAVs (OP model results)

Covariates	**Coef.**	**Z-stat**
Own a vehicle?	-1.386	-3.25
Own at least a vehicle with Level 2 automation?	-1.443	-3.22
Support the use of Speed Governors on all new vehicles?	-0.466	-2.06
Number of fatal (or serious) crashes in past 15 years	-0.170	-1.75
Familiar with UberX or Lyft?	0.336	1.44
Distance from city center (miles)	-0.068	-3.65
Drive alone for work trips?	0.291	1.20
Number of social (or recreational) trips in past 7 days	0.069	1.38
Distance between home and public transit stop (miles)	0.049	2.59
Older than 54 years?	-0.464	-2.17
Male?	-0.428	-2.03
White, European white or Caucasian?	-0.349	-1.37
Bachelor's degree holder	-0.263	-1.32
Full-time worker?	-0.445	-1.65
Single?	-0.431	-1.63
Thresholds	**Coef.**	**Std. Dev.**
Shift closer **vs.** stay at the same location	-4.992	0.589
Stay at the same location **vs.** shift farther	0.103	0.518
Nobs: 1,088 **McFadden's R-Square:** 0.112 **McFadden's adjusted R-Square:** 0.087		

3.6.15 Support for Tolling Policies

Table 3.30 summarizes the OP model estimates of respondents' opinions (i.e., definitely not support, probably not support, do not know, probably support, or definitely support) about three tolling policies.[35] In Policy 1, revenue from tolled congested highways is used to reduce property taxes; in Policy 2, revenue from tolled congested highways is distributed evenly among Texans; in Policy 3, time varying tolls are enabled on all congested roadways. Results indicate that Caucasians who are licensed (or more experienced) drivers and live farther from transit stops,

likely to shift farther from the city center or stay at the same location, but the binary logit model suggests that these individuals are likely to shift. This new binary logit model clarifies that these individuals are expected to shift farther from the city center.

[35] Safety- and tech-based predictors were not used in these models' specifications.

everything else held constant, are likely to show refusal for all tolling policies. Perhaps these individuals are concerned that they would be the primary toll payers,[36] and only others would benefit from these three policies. Interestingly, bachelor's degree holders who live farther from downtown are estimated to support Policies 1 and 2, and full-time workers who have more children in the household are likely to support Policies 2 and 3. Older respondents are predicted to refuse the options presented by Policies 1 and 3. Respondents whose households own at least one vehicle and live in populous areas (everything else held constant) specifically showed refusal for Policy 3, but those who live in neighborhoods with more employed individuals are likely to support this policy.

[36] However, individuals who travel more, all other attributes remaining equal, are likely to support tolling policies 2 and 3.

Table 3.30: Support for tolling policies (OP model results)

Covariates (Model 1: Toll Congested Highways if Reduce Property Tax)	Coef.	Z-stat
Licensed driver for more than 20 years?	-0.462	-2.21
More than 2 social (or recreational) trips in past 7 days	0.295	1.69
Distance between home and public transit stop (miles)	-0.041	-2.53
Distance between home and city's downtown (miles)	0.030	2.09
Household size over 3?	-0.300	-1.50
Number of workers in household	0.228	2.27
Older than 54 years?	-0.474	-1.91
White, European white or Caucasian?	-0.553	-2.37
Bachelor's degree holder	0.365	2.33
Thresholds	**Coef.**	**Std. Dev.**
Definitely not support **vs.** Probably not support	-1.372	0.331
Probably not support **vs.** Do not know	-0.886	0.321
Do not know **vs.** Probably Support	0.268	0.325
Probably support **vs.** Definitely support	1.548	0.345
Nobs: 1,088 **McFadden's R-Square:** 0.049 **McFadden's adjusted R-Square:** 0.041		
Covariates (Model 2: Toll Congested Highways if Distribute Revenues)	**Coef.**	**Z-stat**
Licensed driver (number of years)	-0.043	-5.74
Distance between home and public transit stop (miles)	-0.051	-4.00
Distance between home and city's downtown (miles)	0.026	1.83
Annual VMT (miles)	2.63E-05	2.00
White, European white or Caucasian?	-0.460	-2.93
Number of children in household	0.160	2.05
Bachelor's degree holder	0.227	1.50
Full-time worker?	0.307	1.89
Thresholds	**Coef.**	**Std. Dev.**
Definitely not support **vs.** Probably not support	-1.780	0.280
Probably not support **vs.** Do not know	-1.086	0.272
Do not know **vs.** Probably Support	0.027	0.272
Probably support **vs.** Definitely support	1.596	0.251
Nobs: 1,088 **McFadden's R-Square:** 0.061 **McFadden's adjusted R-Square:** 0.054		

Covariates (Model 3: Time-varying tolls on All Congested Roadways)	Coef.	Z-stat
Own a vehicle?	-0.754	-1.35
More than 2 personal business trips in past 7 days?	0.293	1.14
Distance between home and public transit stop (miles)	-0.024	-1.44
Annual VMT (miles)	1.92E-05	1.48
Age of Respondent (years)	-0.015	-1.84
Have U.S. driver license?	0.342	1.00
White, European white or Caucasian?	-0.903	-4.33
Number of children in household	0.168	1.91
Full-time worker?	0.265	1.66
Population density (per square mile)	-2.51E-04	-1.41
Employed and over 16 years of age (per square mile)	3.96E-04	1.83
Thresholds	**Coef.**	**Std. Dev.**
Definitely not support **vs.** Probably not support	-2.486	0.492
Probably not support **vs.** Do not know	-1.949	0.498
Do not know **vs.** Probably Support	-0.411	0.508
Probably support **vs.** Definitely support	1.185	0.539
Nobs: 1,088 **McFadden's R-Square:** 0.057 **McFadden's adjusted R-Square:** 0.048		

3.7 Conclusions and Future Work

The first survey's results help traffic engineers, planners, and policymakers forecast Americans' long-term (2015 to 2045) adoption of vehicle automation technologies under eight different scenarios based on technology price (5% and 10% annual reduction rates), WTP (0%, 5%, and 10% annual increment rate), and regulations (on ESC and connectivity). The second survey's results offer insights about Texans' WTP for CAV technologies, adoption timing of AVs, home location shifting decisions, adoption rates of SAVs, and opinions about congestion pricing strategies, among many other topics.

The first survey's fleet evolution results indicate that around 98% of the U.S. vehicle fleet is likely to have ESC and connectivity in year 2025 and 2030, respectively, under NHTSA's current and probable regulations. These regulations are likely to accelerate adoption of these technologies by 15 to 20 years, and make U.S. roads safer. At more than 5% WTP increment rate and 5% price reduction rate, all Level 1 technologies are estimated to have adoption rates of more than 90% in 2045. Among Level 1 technologies, TSR is the least appealing (54.4% of respondents reported $0 WTP) for Americans, currently the least adopted (2.1%), and is anticipated to remain least adopted, with adoption rates of 38.1% in 2045 at 5% tech-price reduction and constant WTP. At 5% price reduction and 5% WTP increment rate, however, TSR is estimated to be the fourth-least adopted, with adoption rates of 70%. Blind-spot monitoring and emergency automatic braking are the two most appealing Level 1 technologies for Americans; they are anticipated to be the most and second-most adopted Level 1 technologies (excluding ESC) in 2045 at 5% tech-price reduction and constant WTP, with adoption rates of 53.5% and 51.2%. However, blind-spot monitoring and emergency automatic braking are anticipated to be third-most and most adopted Level 1 technologies in 2045 at 5% price reduction and 5% WTP increment rate, with adoption rates of 73.6% and 77.8%.

More than half of the respondents are not willing to pay anything to add the advanced automation technologies (self-parking valet, and Level 3 and Level 4 automation). Thus, the population-weighted average WTP to add these technologies is less than half of the average WTP of the respondents who indicate non-zero WTP for these technologies. Of the respondents with a non-zero WTP, the average WTP to add connectivity and Level 3 and Level 4 automation are \$110, \$5,551, and \$14,589, respectively. Long-term fleet evolution suggests that Level 4 AVs are likely to represent 24.8% to 87.2% of the nation's light-duty, privately owned vehicle fleet in 2045.[37]

The first survey's opinion-related summaries indicate that around 88.2% of Americans believe that they are great drivers and, surprisingly, around three-quarters enjoy driving a car. Around 60% of the respondents would be uncomfortable in sending AVs out knowing that, as owners, they would be liable for any accident. The area of greatest discomfort for Americans is allowing their vehicle to transmit data to toll operators and insurance companies. Technology companies (62.3%), followed by luxury vehicle manufactures (49.5%), appear to be the top choices of Americans for developing Level 4 AVs. Roughly the same shares of respondents reported WTP of \$0 to use AVs for short-distance (42.5%) or long-distance (40.0%) trips. The average number of long-distance trips (over 50 miles) is reported to increase by 1.3 (per person per month) due to the adoption of AVs.

The results of the second survey suggest that around 41% of Texans are not ready to use SAVs and only 7.3% hope to rely entirely on SAV fleet, even at \$1 per mile. AVs and SAVs are less likely to affect Texans' decisions about moving closer to or farther from the city center: about 81.5% indicated an intention or desire to stay at their current locations. Talking to other passengers and looking out the window are the Texans' top two activity-picks while riding in Level 4 AVs. Affordability and equipment failure are the Texans' top two concerns regarding AVs; the two least concerning aspects are learning how to use AVs and, surprisingly, potential privacy breaches. Texans expect that AVs can help provide better fuel economy and also decrease crashes: 53.9% and 53.1% of the respondents, respectively, indicated that these benefits will be very significant.

Texans' average WTP to save 15 minutes of travel time on a 30-minute one-way trip is \$6.80, but this figure increases to \$9.50 if we remove those respondents with \$0 WTP for this benefit (28.5%). Among those with positive WTP, the average WTPs to ride in Level 4 AVs alone on a one-way trip are \$9.90, \$10.10, and \$18.10 for the shopping, work, and intercity trips, respectively, and these WTPs increase to \$11.80, \$13.60, and \$20.40 for a ride with family. Texans are most likely to support adaptive traffic signal timing and least likely to support real- time adjustment in parking prices (when 80% of vehicles are connected). On average, Texans rank safety as the most important and climate change as the least important area of improvement in automobile technologies.

Using Survey 2 data, OP and IR models were estimated to understand the impact of Texans' demographics, built-environment factors, travel characteristics, and other attributes on their adoption of and interest in CAV technologies and SAVs. Those who support speed regulation strategies (e.g., speed governor on all new vehicles) and have higher household income, other attributes held constant, are estimated to pay more for all levels of automation and connectivity. However, older and more experienced licensed drivers are expected to place lower value on these technologies. Perhaps older individuals are finding it difficult to conceive that CAVs are about to

[37] Lower bound on adoption rate is anticipated at *5% drop in tech prices and constant WTP* and upper bound is forecasted at *10% drop in tech prices and 10% WTP rise.*

hit the roads and licensed drivers who particularly enjoy driving might be worried about sacrificing those elements of driving they find enjoyable. Caucasians' WTP for Level 2 automation and SAV adoption rates are estimated to be lower than for other ethnicities, as was the case for connectivity, implying that non-Caucasians are likely to be early adopters of these technologies. Interestingly, AV adoption timing of those who have higher WTP for AVs is less likely to depend on friends' adoption rates. It is worth noting that even unemployed and lower income households (with annual household income less than $30,000) are estimated to use SAVs more frequently at $1 per mile; perhaps SAVs are affordable for these individuals at this price. Respondents who are familiar with UberX are estimated to use SAVs less frequently at $2 and $3 per mile (more than what carsharing companies and UberX charge). Perhaps those who know about ridesharing services are not willing to pay additional costs to enjoy SAVs' additional utilities (on the top of traditional ridesharing). Bachelor's degree holders, single individuals, and full-time workers who support speed governors, own at least one vehicle with Level 2 automation, have experienced more fatal crashes in past, and live farther from a city center, all other attributes held constant, are likely to shift closer to the city center. Perhaps these individuals are excited about higher density of low-cost SAVs near city center.

These results reflect the current perceptions of Americans (and more explicitly, of Texans). As the public learns more about CAVs and more people gain familiarity with these technologies, these perceptions and potential behavioral responses are apt to change, in some cases rapidly. For example, a large proportion (more than 50%) of individuals who do not want to pay anything for advanced automation technologies may change their perspectives, as the technology becomes proven and they see their neighbors, friends, and co-workers adopt AVs to great success. Alternatively, a well-publicized catastrophe (such as a multi-vehicle, multi-fatality cyber-attack) could set adoption rates back years. As such, more survey work is required elsewhere in the U.S. and other countries, and over time. This is a dynamic stage for an important impending technological shift. Knowledge of the underlying factors across geographies and over time will be important in helping all relevant actors (the public, businesses, regulators, and policymakers) coordinate to enable cost-effective, environmentally sensitive, and operationally efficient transformation of the transportation system.

WTP is typically a function of demographics and built-environment factors and thus is expected to change over the years. Since this study does not consider the evolution of a household's demographic and built-environment characteristics (e.g., change in household size, number of workers, and neighborhood population density), a household's WTP over time is considered to increase at constant annual rates. However, integration of household evolution over the years, followed by behaviorally defensible temporal variation in the households' WTP, can change the estimates of the technology adoption rates. This is a potential future research direction. Lastly, SAVs are likely to change future vehicle ownership patterns; thus, inclusion of SAVs in the simulation framework can be a good extension of this study.

With the survey data and model results in full focus, Chapter 4 reviews the safety benefits of CAVs.

Chapter 4. Safety Benefits of CAVs

This project attempts to comprehensively anticipate the safety benefits of various CV and AV technologies, in combination, and in terms of economic costs and functional life-years saved across the U.S. and Texas. The most recently-available U.S. crash database (the 2013 National Automotive Sampling System (NASS) General Estimates System (GES) was used, and results suggest that advanced CAV technologies may reduce current U.S. crash costs by at least $126 billion per year (not including pain and suffering damages, and other non-economic costs) and functional human-years lost by nearly 2 million (per year). These results rely on three different effectiveness scenarios with market penetration rate of 100% of all CV and AV based safety applications. In order to understand the ramifications of introducing autonomous vehicles (AVs) into the traffic system, this work also develops a microsimulation model that utilizes both human-operated vehicle (HV) and AV driving models, and then estimates the number of vehicle collisions that would occur given different rates of AV market penetration.

According to the 2013 GES crash database, of the eleven safety applications (which were defined by the USDOT and by the research team) or combinations of safety applications, the one with the greatest potential to avoid or mitigate crashes is FCW associated with CACC. A cooperative intersection collision avoidance system (CICAS) also offers substantial safety rewards, with total economic savings over $22 billion each year (and almost 1.24 million years saved). These two safety applications are estimated here to represent over 55% of the total economic costs saved by all eleven combinations of CV and AV technologies, suggesting important directions for government agencies and transportation system designers and planners. These two technologies may most merit priority deployment, incentives policies, and driver/traveler adoption.

We utilized the modeling and simulation software Vissim from the PTV Group, which is an extremely flexible traffic system modeling environment, to implement a custom AV driver behavior through the software's External Driver Module. Currently, it is impossible to directly assess the impacts of AVs on the safety of a traffic system. Primarily because AVs do not yet exist on public roadways, except for a few isolated examples. However, one of the outputs from Vissim is a complete list of the locations and velocities of all vehicles at all times. This information is inserted into the Surrogate Safety Assessment Model (SSAM), which was released by the Federal Highway Administration (FHWA), to help analyze potential conflicts between vehicles. The output of this process is an estimate of how many crashes per year are likely to occur on different road configurations given different rates of AV market penetration.

Using Vissim, the analysis of different network intersections under various conditions of traffic volume and AV concentration was performed. Some of the intersections used for analysis were generated based on the commonly occurring intersection types, while others were modeled on existing highway intersections. Following the analysis completed using Vissim, the SSAM was used to predict and analyze the trends in traffic safety for the conditions and networks under study. Compiling the Vissim microsimulation outputs and SSAM safety prediction outputs, it was observed that, except for minor discrepancies, the use of AVs improved overall traffic system safety as measured by a decrease in "vehicle conflicts" (crashes), as well as the severity of the estimated crashes.

4.1 Introduction

Studies were conducted by different researchers (Najm et al., 2013; Jermakian, 2011) on the potential safety benefits from CV-based safety applications. Rau et al. (2015) extended their research direction into the combination of AV and CV technologies. Due to the lack of records related to the CAV technologies, as far as we know, no studies have been performed to show the economic cost and functional human-years saved by the combination of CV and AV technologies. However, the safety benefits of these advanced transportation technologies are essential for planners to make a schedule of technology spreading.

This project designed a method to estimate the safety benefits of CAV technologies in terms of economic cost and functional human-years by using nationwide crash dataset (2013 GES). In order to calculate the potential impacts of safety applications, mapped to their corresponding crash types, different scenarios of safety application effectiveness were applied.

This chapter is divided into seven sections. Section 4.2 discusses recent literature on traffic safety impact analysis of CAV technologies; benefits of CV technologies and pre-crash scenario identification based on nationwide crash records (GES); CAV technologies mapping to the corresponding crash records; and a safety benefits estimate of CAVs in terms of economic cost and quality life years. In addition, Section 4.2 looks at the safety benefits of combining CV and AV technologies. Section 4.3 through 4.6 then present a simulation framework to estimate the possible effectiveness of CAV technologies under different technology scenarios, and provide an overview of the simulations performed in Vissim of AVs and HVs. In general, the results of this work support the conclusion that AVs lead to safer roads, both in terms of the number and severity of collisions. However, the data suggests a need to improve the driver models created to simulate both AVs and HVs in Vissim, in order to test a large range of networks and scenarios. Section 4.7 concludes with a recommendations and ideas for further work.

4.2 Literature Review

Advanced transport technologies, including CV technology (e.g., vehicle-to-vehicle [V2V] and vehicle-to-infrastructure [V2I]) and AV technology, have a promising future in improving traveler safety by warning drivers of dangerous conditions and/or taking the control of automated (including semi-automated) vehicles.

In terms of V2V technology, forward collision warning (FCW) is a relatively simple application based on camera or radar sensor that detects an impending collision by recognizing the speed, acceleration, and locations of nearby vehicles and providing the FCW-equipped driver with warnings to avoid a possible crash (Harding et al., 2014). This will reduce some of the most common crash types, including rear-end crashes. If the vehicle also has automatic emergency braking (AEB) enabled, the vehicle can self-slow or self-stop. If automated steering is onboard, the vehicle can self-shift laterally to avoid collisions.

In comparison, CICAS is a special V2I safety application that moderates the count and severity of intersection-related crashes by warning drivers about likely violations of traffic control devices and then helping drivers avoid the collision (Misener, 2010).

Adaptive cruise control (ACC) requires relatively minimal AV technology on board, so that it can detect a vehicle immediately ahead (in the same lane) of a vehicle and adjust the latter’s speed to maintain adequate distance from the vehicle in front. Cooperative adaptive cruise control (CACC) is an extension to the ACC, aiming to increase traffic throughput by safely permitting shorter following distances between vehicles (Jones, 2013). Such applications are expected to largely improve roadway safety while saving vehicle owners and others a great deal of money, pain, and suffering. This report estimates the safety benefits of advanced vehicle technologies in monetary and life-year terms, after summarizing relevant literature on V2V, V2I, and AV technologies.

4.2.1 Safety Impacts of CV Technologies

There has been solid investigation into the safety impacts for V2V- and V2I-based safety applications over the past 10 or so years. In 2006, the UNHTSA entered into cooperative research agreements for Advanced Crash Avoidance Technologies (ACAT) with multiple manufacturers and research teams, including Honda, Volvo, Ford, General Motors, the University of Michigan, and the Virginia Tech Transportation Institute. Those agreements focused on evaluating the safety benefits of several advanced transport technologies by creating an original simulation method, the Safety Impact Methodology (SIM) (Funke et al., 2011). The SIM investigated the safety benefits of advanced collision mitigation braking systems, lane departure warning (LDW) systems, and the pre-collision safety system, by integrating historical crash data (from the U.S.) and naturalistic driving data to populate the simulation model.

Gordon et al. (2010) focused on crashes occurring after a subject vehicle exits the travel lane and developed the target crash types based mainly on the NASS GES and the NASS Crashworthiness Data System (NASS CDS) data sets to investigate the system effectiveness of LDW. Their results suggest that use of LDW systems can reduce 47% of all lane-departure-related crashes, corresponding to 85,000 crashes annually.

Perez et al. (2011) identified backing-up crash scenarios from national and state crash data sources and estimated that the backing-crash countermeasures (like backup collision intervention, via automated braking) could prevent almost 65,000 backup crashes a year (64,823 estimated), among the over 200,000 (201,583) backing-up crashes (typically in parking spaces and at driveways) that occurred in the U.S. in 2004.

Wilson et al. (2007) collected driving data from 78 U.S participants to evaluate the performance and safety benefits of road departure crash warning (RDCW) technology. With the RDCW activated, a 10% to 60% reduction in departure conflict frequency was observed at speeds above 55 mph. With an assumption of 100% deployment and 100% device availability, an annual reduction of 9,400 to 74,800 U.S. road-departure crashes (all at high speeds) was predicted.

4.2.2 Safety Benefits of CV Technologies Based on Pre-crash Scenarios

Pre-crash scenarios depict vehicle movements and the critical event immediately prior to a crash, which enables researchers to determine which traffic safety issues should be of the first priority and determine whether to investigate and design countermeasures to avoid them, or mitigate their severity if they cannot be avoided. Najm et al. (2007) defined a new typology of 37 pre-crash scenarios for crash avoidance research based on the 44-crash typology generated by General Motors in 1997 and pre-crash scenarios typology devised by USDOT in his 2003 report (Najm, 2003). His new typology (shown as Table 4.1) utilizes the GES crash database, since it is updated annually, is nationally representative, and offers important descriptors for identifying pre-crash events; thus, it is the best available source for identification and description. The coding schemes enabled the researchers to identify each pre-crash scenario leading to all single-vehicle and multi-vehicle crashes based on GES variables and codes.

Based on the updated pre-crash scenarios, Najm et al. (2010) investigated V2V and V2I systems and the crash types whose frequencies may be affected by such applications. They estimated that V2V systems, such as FCW, blind spot warning (BSW), and lane change warning (LCW), can serve as primary crash countermeasures, reducing U.S. light-duty vehicle-involved crashes by 76%. They further estimated that V2I systems, such as curve speed warning (CSW), red light violation warning system (RLVW), and stop sign violation warning (SSVW), if deployed anywhere they could be useful, could address 25% of all light-duty-vehicle crashes in the U.S.

At the same time, Jermakian (2011) estimated the maximum potential safety benefits for U.S. crash reductions for four crash avoidance technologies based on the updated pre-crash scenarios by Najm (2007): side view assist, FCW, LDW, and adaptive headlights. Najm extracted crash records from the 2004–2008 NASS GES and FARS data sets in order to calculate the frequency of all related crash types. Najm estimated that FCW holds the greatest potential for preventing crashes of any severity, up to 1.2 million crashes per year in the U.S., or 20% of the annual 5.8 million police-reported crashes. LDW appeared relevant for 179,000 crashes per year, but these can be quite severe, so his total estimate from implementation of LDW was a savings of up to 7,500 fatal crashes, or 4% of all lane-departure-related crashes per year. He also estimated that side view assist and adaptive headlights could prevent 395,000 and 142,000 crashes per year, or 24% of lane-changing-related crashes and 4% of all front-to-rear, single-vehicle, and sideswipe same-direction crashes.

4.2.3 Safety Impacts of Combining CV and AV Technologies

More recently, Rau et al. (2015) developed a method to determine crashes that can be addressed by AV technologies by mapping specific AV-based safety applications to five layers of crash information, including crash location, pre-crash scenario details, driving conditions, travel speeds, and driver conditions. Their study results mapped crashes to several Level 2, 3, and 4 automation technologies (using NTHSA’s 2013 definitions) and various AV safety applications, including ACC and AEB. But they did not take the next step: to anticipate crash reductions. Schoettle and Sivak (2015) conducted a preliminary analysis of the cumulative on-road safety record of self-driving vehicles for three companies (Google, Delphi, and Audi). Despite the low accumulated self-driving distance and limited driving conditions (e.g., avoiding snowy areas), the results indicated that self-driving vehicles were not responsible for any fault in the crashes they were involved in, and that the overall severity of crash-related injuries had been lower than the conventional vehicles.

In reality, the safety benefits of combining CV and AV technologies are important for many more crashes, but detailed work in this area has not yet been undertaken or at least not published. Driver error is considered a major culprit in over 90% of all road crashes (NHTSA, 2008), and Singh (2015) recently estimated that 94% of public roadway crashes can be assigned to human errors based on statistical results he derived from the 2005 to 2007 National Motor Vehicle Crash Causation Survey. These driver-error related crashes could be reduced by 100% or more in terms of cost to society by the partially and fully AVs, which was estimated in the Boston Consulting Group’s research into Advanced Driver Assistance Systems (2015). This report estimates the safety benefits from CV and AV technology combinations, rather than considering only V2V or V2I technology, in the absence of driving automation. These combinations will reduce the impact of human error during the driving process and should improve overall traffic safety, unless, of course, travelers (both motorized and non-motorized) abuse the system, by becoming much more reckless in their travel behaviors.

4.3 Using Pre-Crash Scenarios to Estimate CAV-Technologies Safety Benefits

In this section, Najm's (2007) latest pre-crash typology is presented first to help map the V2V, V2I, and AV safety applications to specific crash types. In this way, safety benefits for each application can be estimated, using economic costs and functional-years lost per typical crash of each variety. The final part of this section introduces three technology-effectiveness scenarios, to reflect uncertainty in how many crashes will benefit from such technologies and hopefully cover the range of the total economic benefits and quality-life-years to be saved by the various CV and AV applications.

4.3.1 Typology of Pre-Crash Situations

As we mentioned above, pre-crash scenario typology, based on 2004 GES crash database, was used by several researchers to estimate the safety impacts of advanced transportation technologies in terms of economic cost and quality-life-years (Najm, 2010 and Jermakian, 2011). In this report, the same pre-crash typology is used, but is based on 2013 GES crash database. The following content will clarify the differences between 2004 and 2013 GES crash database.

The main variables used in the pre-crash scenario typology in the 2004 GES crash database include Critical Event (P_CRASH2), Vehicle Maneuver (MANEUV_I), First Harmful Event (EVENT1_I), and Crash Type (ACC_TYPE).

The Critical Event (P_CRASH2) variable depicts the critical event, which is coded for each vehicle, and identifies the circumstances leading to the vehicle's first impact in the crash. The pre-crash scenario Vehicle Failure, for example, has the identification code P_CRASH=1-4.

The Vehicle Maneuver (MANEUV_I) variable represents vehicle maneuver, which describes the last action this vehicle's driver engaged in either immediately before the impact or just before the driver recognized the impending danger.

Other variables used in the 2004 GES pre-crash scenarios are presented. The First Harmful Event (EVENT1_I) variable describes the first injurious or damaging event of the crash, and the Crash Type (ACC_TYPE) variable specifies crash type of the vehicle involved based on the first harmful event and the pre-crash circumstances. Typical crash types include Drive Off Road; Control/Traction Loss; and Avoid Collision with Vehicle, Pedestrian, Animal. The Violations Charged (MVIOLATN) variable indicates which violations are charged to the drivers, which will be used to identify the Running Red Light and Running Stop Sign pre-crash scenarios. The Traffic Control Device (TRAF_CON) depicts whether or not traffic control devices were present for a motor vehicle and the type of traffic control device.

However, several variables and their value meanings differ between 2004 GES and 2013 GES due to the changes of data coding (NHTSA, 2014). Those variables include Traffic Control Device, Violations Charged, and First Harmful Event. In addition, the variable describing the vehicle role in crashes was not used in the 2013 GES records, which does critically impact our safety benefits analysis. (The vehicle role variable only influences the exact frequencies of pre-crash scenarios with rear-end crashes, but not the total frequencies of rear-end crashes addressed on corresponding safety applications).

In coding the 2013 NASS GES data to identify passenger-vehicle crash counts, crash records differed between the GES Accident file and Vehicle file. There were incomplete and incorrect crash records in the 2013 GES crash database. For example, VE_FORMS (variable indicates vehicle numbers involved in a crash) was 4, but the VEH_NO (variable describes vehicle ID in that crash) only had 1, 2, and 3, which means incorrect crash records. After eliminating those incomplete and incorrect data records, 34,606 (99.5% of total 34,793 crash records) valid crash records (involving at least one light-duty vehicle) remained in the 2013 NASS GES files. When sampling weights are applied, these records represent approximately 5,508,000 crashes and 20,503 fatalities nationwide, including 1,608,000 single-vehicle crashes and 3,900,000 multi-vehicle crashes.

In our study, only light-duty vehicle crashes (i.e., those involving passenger cars, sports utility vehicles, vans, minivans, and pickup trucks) are investigated. The GES variables of Body Type and Special Use were queried to identify all light-duty vehicles. Body Type was set to include types 01-22, 28-41, and 45-49. Special Use was set equal to 0. Furthermore, in order to eliminate double counting of crashes in each scenario, pre-crash scenarios were updated by removing all scenarios in the number order via a process of elimination; in this way, the resulting frequency distribution sums to 100%. For example, one crash record can be assigned to pre-crash scenarios 1, 5, and 10, but this crash record will only belong to pre-crash scenario 1 because of its number order.

The 37 scenario identification codes can be used to select records from the GES database, and all pre-crash scenarios can be categorized into crash types, a more general term to segment or distinguish crashes. Table 4.1 illustrates each pre-crash scenario and the crash types to which they belong.

Table 4.1: Mapping of crash types to new pre-crash scenario typology

No.	Pre-Crash Scenario	Crash Type
1	Vehicle failure	Run-off-road
2	Control loss with prior vehicle action	
3	Control loss without prior vehicle action	
4	Running red light	Crossing paths
5	Running stop sign	
6	Road edge departure with prior vehicle maneuver	Run-off-road
7	Road edge departure without prior vehicle maneuver	
8	Road edge departure while backing up	
9	Animal crash with prior vehicle maneuver	Animal
10	Animal crash without prior vehicle maneuver	
11	Pedestrian crash with prior vehicle maneuver	Pedestrian
12	Pedestrian crash without prior vehicle maneuver	
13	Pedalcyclist crash with prior vehicle maneuver	Pedalcyclist
14	Pedalcyclist crash without prior vehicle maneuver	
15	Backing up into another vehicle	Backing
16	Vehicle(s) turning – same direction	Lane change
17	Vehicle(s) changing lanes – same direction	
18	Vehicle(s) drifting – same direction	
19	Vehicle(s) parking – same direction	Parking
20	Vehicle(s) making a maneuver – opposite direction	Opposite direction
21	Vehicle(s) not making a maneuver – opposite direction	
22	Following vehicle making a maneuver	Rear-end
23	Lead vehicle accelerating	
24	Lead vehicle moving at lower constant speed	
25	Lead vehicle decelerating	
26	Lead vehicle stopped	
27	LTAP/OD at signalized junctions	Crossing paths
28	Vehicle turning right at signalized junctions	
29	LTAP/OD at non-signalized junctions	
30	Straight crossing paths at non-signalized junctions	
31	Vehicle(s) turning at non-signalized junctions	
32	Evasive action with prior vehicle maneuver	Run-off-road
33	Evasive action without prior vehicle maneuver	
34	Non-collision incident	Non-collision
35	Object crash with prior vehicle maneuver	Object
36	Object crash without prior vehicle maneuver	
37	Other	Other

Source: Najm et al., 2007

4.3.2 Monetary and Non-Monetary Measures of Crash Costs

Economic cost is a common term in transportation engineering, used to estimate the monetary loss of crashes and related events. Functional-years lost, a measure that provides a non-monetary measure of time lost as a result of motor vehicle crashes, represents the sum of the years of life lost to fatal injuries and years of functional capacity (much like a reasonable quality of life) lost to non-fatal injuries (Miller, 1991). Economic costs are defined as goods and services that must be purchased or productivity that is lost as a result of motor vehicle crashes (Blincoe, 2015). This includes lost productivity (at paid work and at home, for example), medical costs, legal and court costs, emergency service costs, insurance administration costs, travel delay, property damage, and workplace losses.

With Najm's (2007) identification codes of pre-crash scenarios used in the 2004 GES crash database, the frequency of each pre-crash scenario and the injury severity rating to a person can be derived using the KABCO scale in the 2013 GES crash records. The KABCO scale records injury severity as resulting in a death (K, for killed), an incapacitating injury (A), a non-incapacitating injury (B), a possible injury (C), or no apparent injury/property-damage only (O).

The KABCO scale must be translated into the Maximum Abbreviated Injury Scale (MAIS) to estimate economic costs and functional-years lost. MAIS levels of injury severity (for the crash victim who suffered the greatest injury) have seven categories, ranging from uninjured (MAIS0) to fatal (MAIS6), thus differing somewhat from the KABCO scale, which has six categories from fatal (K) to injury severity unknown (ISU). Here, Blincoe's (2015) KABCO/MAIS translator, designed on the basis of 2000–2008 NASS CDS data, was employed, to convert all GES injury severities from KABCO to MAIS.

The economic unit costs of reported and unreported crashes were calculated in U.S. dollars for the year 2010 for each level of MAIS injury severity, and these were used to convert the MAIS injury severity to economic costs. Because the economic cost estimates in our study are based on the 2013 GES crash database, a cumulative rate of inflation between 2010 and 2013 was used (6.8% over 3 years). In total, the unit costs of a crash where no one was injured (MAIS0) thus becomes $3,042 in 2013 dollars, a crash victim suffering minor injury (MAIS1) is valued at $19,057, one experiencing moderate injury crash (MAIS2) is valued at $59,643, a serious injury (MAIS3) is valued at $194,662, a severe injury (MAIS4) is $422,231, and a critical injury (MAIS5) is $1,071,165, and fatal injury (MAIS6) is estimated to represent $1,496,840 in economic loss.

Functional-years lost is a non-monetary measure that calculates the years of life lost due to fatal injury and the years of functional capacity lost due to non-fatal injuries (Najm, 2007). This assigns a different value to the relative severity of injuries suffered from motor vehicle crashes. The numbers between injury severity on the basis of MAIS scale and the functional-years lost are 0.07, 1.1, 6.5, 16.5, 33.3, and 42.7 functional-years lost, corresponding to the MAIS0 through MAIS6.

4.3.3 Mapping CAV Safety Applications to Specific Pre-Crash Scenarios

The first step of this estimation process involves mapping each advanced safety application to specific, applicable pre-crash scenarios. Najm et al. (2013) recently mapped many safety applications using V2V technology, including FCW, intersection movement assist (IMA), BSW, LCW, do not pass warning (DNPW), and control loss warning (CLW), to 17 pre-crash scenarios that can be somewhat addressed by V2V technology. For example, FCW can reduce the frequency of read-end crash types, including the pre-crash scenarios of Following Vehicle Making a Maneuver, Lead Vehicle Accelerating, Lead Vehicle Moving at Lower Constant Speed, Lead

Vehicle Decelerating, and Lead Vehicle Stopped. With the help of AEB, the injury severity of rear-end crashes can be further mitigated by slowing the vehicle in time.

IMA can be mapped to certain crossing-paths crash types, including the pre-crash scenarios of Left Turn Across Path of Opposite Direction (LTAP/OD) at Non-Signalized Junctions, Straight Crossing Paths at Non-Signalized Junctions, and Vehicle(s) Turning at Non-Signalized Junctions. CICAS warns drivers of impending violations at traffic signals and stop signs (Maile and Delgrossi, 2009). Compared with IMA, CICAS has a more powerful function, which warns drivers of running a red light or stop sign or of red-right or stop-sign runners; CICAS can also coordinate intersection movements, and thus take the place of the IMA, RLVW, and SSVW systems. Therefore, CICAS addresses the following pre-crash scenarios: Running Red Light, Running Stop Sign, LTAP/OD at Signalized Junctions, Vehicle Turning Right at Signalized Junctions, LTAP/OD at Non-Signalized Junctions, Straight Crossing Paths at Non-Signalized Junctions, and Vehicle(s) Turning at Non-Signalized Junctions.

BSW and LCW technologies will benefit the Vehicle(s) Turning – Same Direction, Vehicle(s) Changing Lanes – Same Direction, and Vehicle(s) Drifting – Same Direction pre-crash scenarios. DNPW should improve safety in Vehicle(s) Making a Maneuver – Opposite Direction and Vehicle(s) Not Making a Maneuver – Opposite Direction pre-crash situations. CLW can help prevent or mitigate the severity of Vehicle Failure, Control Loss With Prior Vehicle Action, and Control Loss Without Prior Vehicle Action pre-crash situations.

RDCW is a combined application of LDW and CSW, which can warn drivers of impending road departure (Wilson et al., 2007). The major function of the LDW is to monitor the vehicle's lane position, lateral speed, and available maneuvering room by using a video camera to estimate the distances between the vehicle and the left and right lane boundaries, and is able to alert a driver when the vehicle seems likely to depart the lane. The main contribution of CSW is monitoring vehicle speed and upcoming road curvature and alerting a driver when the vehicle is approaching the upcoming curve at an unsafe speed. The RDCW application has the potential to improve the traffic safety of the pre-crash scenarios of Road Edge Departure With Prior Vehicle Maneuver, Road Edge Departure Without Prior Vehicle Maneuver, and Road Edge Departure While Backing Up, judging by their definitions.

The vehicle-to-pedestrian (V2Pedestrian) and vehicle-to-pedalcyclist (V2Pedalcyclist) communication safety applications have the potential to detect a pedestrian or bicyclist in a possible crash situation with a vehicle and warn the driver (Harding et al., 2014). To be more specific, the pedestrians/bicyclists can carry devices (such as mobile phones) that can send out a safety signal using dedicated short-range communications (DSRC) to communicate with in-vehicle DSRC devices, so both the pedestrian/cyclist and the driver could be warned if a possible conflict arises. Four pre-crash scenarios can be addressed by this safety application: Pedestrian Crash With Prior Vehicle Maneuver, Pedestrian Crash Without Prior Vehicle Maneuver, Pedalcyclist Crash With Prior Vehicle Maneuver, and Pedalcyclist Crash Without Prior Vehicle Maneuver.

The safety applications described above emphasize CV technologies, such as V2V and V2I. AV technology is rapidly advancing and will also play a key safety role by reducing or even eliminating many human-related factors leading to crashes, and greatly improve warning response times and response decisions. CACC, an extension of ACC, uses radar and LIDAR measurements to derive the range to the vehicle in front; the preceding vehicle's acceleration is used in a feed-forward loop (Jones, 2013). This enhanced safety application, associated with FCW, can further reduce the number of rear end crashes, including the pre-crash scenarios of Following Vehicle

Making a Maneuver, Lead Vehicle Accelerating, Lead Vehicle Moving at Lower Constant Speed, Lead Vehicle Decelerating, and Lead Vehicle Stopped. Therefore, a combination of V2V and AV technologies (FCW and CACC) has been identified to address pre-crash scenarios of Following Vehicle Making a Maneuver, Lead Vehicle Accelerating, Lead Vehicle Moving at Lower Constant Speed, Lead Vehicle Decelerating, and Lead Vehicle Stopped.

Lane-keeping assist (LKA) technology alerts the driver when lane deviations are detected. The system can also work in conjunction with the radar cruise control system to help the driver steer and keep the vehicle on course (Bishop, 2005). The LKA technology maps to pre-crash scenarios of Road Edge Departure With Prior Vehicle Maneuver, Road Edge Departure Without Prior Vehicle Maneuver, and Road Edge Departure While Backing Up, which are also addressed by the RDCW. Therefore, a combination of V2I and AV technologies (RDCW and LKA) has been mapped to these pre-crash scenarios.

ESC is another important AV safety application technology. ESC is an onboard car safety system that maintains the stability of a car during critical maneuvering and corrects potential under-steering or over-steering, which can help prevent crashes that result from loss of control (Lie et al., 2006). AEB can use radar, laser, or video to detect when obstructions or pedestrians are present and be automatically applied to avoid the collision or at least to mitigate the effects for the host and target vehicles. The pre-crash scenarios of Animal Crash With Prior Vehicle Maneuver, Animal Crash Without Prior Vehicle Maneuver, Evasive Action With Prior Vehicle Maneuver, Evasive Action Without Prior Vehicle Maneuver, Object Crash With Prior Vehicle Maneuver, and Object Crash Without Prior Vehicle Maneuver could be mapped to the ESC and AEB. Although other pre-crash scenarios (e.g., scenarios involving pedestrian) may be also related to these safety applications, in order to avoid double counting, the combination of ESC and AEB can be mapped only to the six pre-crash scenarios mentioned above. The pre-crash scenario Backing Up Into Another Vehicle can be addressed by the backup collision intervention (BCI) that intelligently senses what the driver may miss when backing up and can even apply the brakes momentarily to get the driver's attention.

Not all pre-crash scenarios listed in Table 4.2 have been mapped to specific safety applications. Given the uncertain characteristics of the pre-crash scenarios of Non-Collision Incident and Other, there is no corresponding safety application. As for the Non-Collision Incident, an example scenario is that vehicle is going straight in a rural area, in daylight, under clear weather conditions, at a non-junction location with a posted speed limit of over 55 mph, when fire abruptly starts. In this situation, none of the safety applications mentioned above can prevent the accident or mitigate the accident severity. On the other hand, the Other pre-crash scenario may benefit from those safety applications, so the combined impacts of the CV- and AV-based safety applications will be exerted on this scenario.

Table 4.2 lists all the pre-crash scenarios based on 2013 GES crash records and their corresponding CAV safety applications.

Table 4.2: Mapping pre-crash scenarios to CAV technologies based on 2013 GES

No.	Pre-Crash Scenario	Mapping Safety Applications
1	Vehicle failure	CLW
2	Control loss with prior vehicle action	CLW
3	Control loss without prior vehicle action	CLW
4	Running red light	CICAS
5	Running stop sign	CICAS
6	Road edge departure with prior vehicle maneuver	RDCW & LKA
7	Road edge departure without prior vehicle maneuver	RDCW & LKA
8	Road edge departure while backing up	RDCW & LKA
9	Animal crash with prior vehicle maneuver	AEB & ESC
10	Animal crash without prior vehicle maneuver	AEB & ESC
11	Pedestrian crash with prior vehicle maneuver	V2P
12	Pedestrian crash without prior vehicle maneuver	V2P
13	Pedalcyclist crash with prior vehicle maneuver	V2Ped
14	Pedalcyclist crash without prior vehicle maneuver	V2Ped
15	Backing up into another vehicle	BCI
16	Vehicle(s) turning – same direction	BSW & LCW
17	Vehicle(s) changing lanes – same direction	BSW & LCW
18	Vehicle(s) drifting – same direction	BSW & LCW
19	Vehicle(s) parking – same direction	SPVS
20	Vehicle(s) making a maneuver – opposite direction	DNPW
21	Vehicle(s) not making a maneuver – opposite direction	DNPW
22	Following vehicle making a maneuver	FCW & CACC
23	Lead vehicle accelerating	FCW & CACC
24	Lead vehicle moving at lower constant speed	FCW & CACC
25	Lead vehicle decelerating	FCW & CACC
26	Lead vehicle stopped	FCW & CACC
27	LTAP/OD at signalized junctions	CICAS
28	Vehicle turning right at signalized junctions	CICAS
29	LTAP/OD at non-signalized junctions	CICAS
30	Straight crossing paths at non-signalized junctions	CICAS
31	Vehicle(s) turning at non-signalized junctions	CICAS
32	Evasive action with prior vehicle maneuver	AEB & ESC
33	Evasive action without prior vehicle maneuver	AEB & ESC
34	Non-collision incident	None
35	Object crash with prior vehicle maneuver	AEB & ESC
36	Object crash without prior vehicle maneuver	AEB & ESC
37	Other	Combined Impacts of Safety Applications

4.3.4 Effectiveness Assumptions of Safety Applications

Mapping the technologies to the target pre-crash scenarios is not enough to estimate the safety benefits. We need to determine the effectiveness of each technology for the corresponding pre-crash scenario(s) to complete the safety benefits analysis. The ideal way to obtain the actual effectiveness of technologies is to take advantage of field tests and collect data from the real-life operation; however, these technologies are not yet implemented in most cars, so there is no available field test data. Therefore, the research team made certain assumptions about the effectiveness of safety applications in related pre-crash scenarios.

Effectiveness discussed here depicts the decrease of fatal crashes—(K) on the KABCO scale—with 100% market penetration of all CV and AV technologies. The effectiveness of safety applications for other severity types will be increased by 10% compared with their next lower injury severity levels. The maximum effectiveness is 100%, which means the technology can 100% avoid corresponding crashes. The effectiveness of safety applications will be set at a constant rate in the Injury Severity Unknown category, as well as in the Other pre-crash scenario. Three different scenarios are considered: conservative, moderate, and aggressive effectiveness.

For example, in the conservative scenario, the effectiveness of the combination of FCW and CACC on rear-end crashes is assumed to be 70% in terms of fatal crashes. According to our regulation, its effectiveness for the incapacitating injury (A), non-incapacitating injury (B), possible injury (C), or uninjured (O) is 80%, 90%, 100%, and 100%, respectively. In addition, the effectiveness of the safety applications on their corresponding pre-crash scenarios is uniformly set up to 30% in the conservative effectiveness scenario, as well as the combined effectiveness of all technologies on the Other pre-crash scenario. Table 4.3 presents the effectiveness assumptions of all three scenarios.

The effectiveness assumptions will be applied to the original frequency of severity in terms of the KABCO scale, and then translated to the MAIS scale to complete the safety benefits estimate.

Table 4.3: Effectiveness assumptions of safety applications in three scenarios

Safety Application	Scenario: Conservative						Scenario: Moderate						Scenario: Aggressive					
	K	A	B	C	O	U	K	A	B	C	O	U	K	A	B	C	O	U
FCW & CACC	0.7	0.8	0.9	1	1	0.3	0.8	0.9	1	1	1	0.4	0.9	1	1	1	1	0.5
CICAS	0.5	0.6	0.7	0.8	0.9	0.3	0.6	0.7	0.8	0.9	1	0.4	0.8	0.9	1	1	1	0.5
CLW	0.4	0.5	0.6	0.7	0.8	0.3	0.5	0.6	0.7	0.8	0.9	0.4	0.6	0.7	0.8	0.9	1	0.5
RDCW & LKA	0.3	0.4	0.5	0.6	0.7	0.3	0.5	0.6	0.7	0.8	0.9	0.4	0.7	0.8	0.9	1	1	0.5
SPVS	0.6	0.7	0.8	0.9	1	0.3	0.7	0.8	0.9	1	1	0.4	0.8	0.9	1	1	1	0.5
BSW &LCW	0.7	0.8	0.9	1	1	0.3	0.8	0.9	1	1	1	0.4	0.9	1	1	1	1	0.5
DNPW	0.6	0.7	0.8	0.9	1	0.3	0.7	0.8	0.9	1	1	0.4	0.8	0.9	1	1	1	0.5
AEB & ESC	0.3	0.4	0.5	0.6	0.7	0.3	0.4	0.5	0.6	0.7	0.8	0.4	0.5	0.6	0.7	0.8	0.9	0.5
V2P	0.4	0.5	0.6	0.7	0.8	0.3	0.5	0.6	0.7	0.8	0.9	0.4	0.6	0.7	0.8	0.9	1	0.5
BCI	0.7	0.8	0.9	1	1	0.3	0.8	0.9	1	1	1	0.4	0.9	1	1	1	1	0.5
V2Pedalcyclist	0.3	0.4	0.5	0.6	0.7	0.3	0.4	0.5	0.6	0.7	0.8	0.4	0.5	0.6	0.7	0.8	0.9	0.5
Combined Impacts of Safety Applications	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5

Key:
(K) fatality; (A) incapacitating injury; (B) non-incapacitating injury; (C) possible injury; (O) no apparent injury/property-damage only;
(U) severity unknown
Red = low impact (0 to 0.4)
Yellow = medium impact (0.5 to 0.9)
Green = high impact (1)

4.3.5 Summary Results

Table 4.4 lists pre-crash scenarios of all light-vehicle crashes by occurrence frequency. Thirty-six pre-crash scenarios represent 99.8% of all 2013 GES passenger-vehicle crashes. The top-five (most common) pre-crash scenarios are Lead Vehicle Moving at Lower Constant Speed, Road Edge Departure Without Prior Vehicle Maneuver, Control Loss Without Prior Vehicle Action, Evasive Action Without Prior Vehicle Maneuver, and Non-Collision Incident, accounting for 47% of all police-reported, light-duty-vehicle crashes.

Tables 4.5 through 4.9 show the pre-crash scenarios in terms of the resulting loss: $170 billion in total economic cost and 2,318,000 functional-years lost. The tables break down the safety benefits of all smart-vehicle-technology applications, according to each pre-crash scenario under each of the three different effectiveness scenarios.

Advanced transport technologies are estimated to save from $127 to $151 billion in economic costs each year in the U.S., and as much as 1,422,600 to 1,652,200 functional human-years. Among the eleven safety application combinations, the FCW associated with CACC is estimated to have the greatest potential to reduce crash costs, by preventing or mitigating the severity of crossing-path crashes, resulting in an estimated annual (economic) savings of at least $53 billion, alongside 497,100 functional years. This technology is followed by CICAS, in terms of savings benefits. Taken together, they comprise 60%, 57%, and 55% of total economic costs from crashes, under the conservative, moderate, and aggressive effectiveness scenarios, respectively.

Table 4.4: Frequency of pre-crash scenarios of all light-vehicle crashes based on 2013 GES crash records

No.	Pre-Crash Scenario	Frequency	Relative Frequency
1	Vehicle failure	44,000	0.80%
2	Control loss with prior vehicle action	65,000	1.18%
3	Control loss without prior vehicle action	393,000	7.14%
4	Running red light	192,000	3.49%
5	Running stop sign	36,000	0.65%
6	Road edge departure with prior vehicle maneuver	85,000	1.54%
7	Road edge departure without prior vehicle maneuver	441,000	8.01%
8	Road edge departure while backing up	73,000	1.33%
9	Animal crash with prior vehicle maneuver	3,000	0.05%
10	Animal crash without prior vehicle maneuver	297,000	5.39%
11	Pedestrian crash with prior vehicle maneuver	27,000	0.49%
12	Pedestrian crash without prior vehicle maneuver	42,000	0.76%
13	Pedalcyclist crash with prior vehicle maneuver	127,000	2.31%
14	Pedalcyclist crash without prior vehicle maneuver	120,000	2.18%
15	Backing up into another vehicle	22,000	0.40%
16	Vehicle(s) turning – same direction	279,000	5.07%
17	Vehicle(s) changing lanes – same direction	247,000	4.48%
18	Vehicle(s) drifting – same direction	4,000	0.07%
19	Vehicle(s) parking – same direction	95,000	1.72%
20	Vehicle(s) making a maneuver – opposite direction	91,000	1.65%
21	Vehicle(s) not making a maneuver – opposite direction	1,079,000	19.59%
22	Following vehicle making a maneuver	202,000	3.67%
23	Lead vehicle accelerating	3,000	0.5%
24	Lead vehicle moving at lower constant speed	239,000	4.34%
25	Lead vehicle decelerating	116,000	2.11%
26	Lead vehicle stopped	295,000	5.36%
27	LTAP/OD at signalized junctions	199,000	3.61%
28	Vehicle turning right at signalized junctions	320,000	5.81%
29	LTAP/OD at non-signalized junctions	125,000	2.27%
30	Straight crossing paths at non-signalized junctions	78,000	1.42%
31	Vehicle(s) turning at non-signalized junctions	9,000	0.16%
32	Evasive action with prior vehicle maneuver	1,000	0.02%
33	Evasive action without prior vehicle maneuver	10,000	1.18%
34	Non-collision incident	11,000	0.20%
35	Object crash with prior vehicle maneuver	17,000	3.41%
36	Object crash without prior vehicle maneuver	36,000	0.65%
37	Other	85,000	1.54%
	Totals	***5,508,000***	***100%***

Table 4.5: Annual economic costs and functional-years lost in all pre-crash scenarios (based on 2013 GES crash records)

No.	Pre-Crash Scenario	Economic Costs (Millions of 2013 Dollars)	Functional-years Lost (Years)
1	Vehicle failure	$1,585	25,000
2	Control loss with prior vehicle action	$14,425	290,000
3	Control loss without prior vehicle action	$7,570	103,000
4	Running red light	$1,194	14,000
5	Running stop sign	$1,958	34,000
6	Road edge departure with prior vehicle maneuver	$13,419	264,000
7	Road edge departure without prior vehicle maneuver	$667	5,000
8	Road edge departure while backing up	$27	1,000
9	Animal crash with prior vehicle maneuver	$3,359	29,000
10	Animal crash without prior vehicle maneuver	$2,653	62,000
11	Pedestrian crash with prior vehicle maneuver	$5,086	125,000
12	Pedestrian crash without prior vehicle maneuver	$925	15,000
13	Pedalcyclist crash with prior vehicle maneuver	$1,221	24,000
14	Pedalcyclist crash without prior vehicle maneuver	$2,094	14,000
15	Backing up into another vehicle	$2,983	38,000
16	Vehicle(s) turning – same direction	$550	6,000
17	Vehicle(s) changing lanes – same direction	$6,948	60,000
18	Vehicle(s) drifting – same direction	$5,222	41,000
19	Vehicle(s) parking – same direction	$952	26,000
20	Vehicle(s) making a maneuver – opposite direction	$6,087	124,000
21	Vehicle(s) not making a maneuver – opposite direction	$24	1,000
22	Following vehicle making a maneuver	$2,496	29,000
23	Lead vehicle accelerating	$383	4,000
24	Lead vehicle moving at lower constant speed	$10,826	113,000
25	Lead vehicle decelerating	$15,545	140,000
26	Lead vehicle stopped	$27,304	293,000
27	LTAP/OD at signalized junctions	$884	6,000
28	Vehicle turning right at signalized junctions	$5,102	70,000
29	LTAP/OD at non-signalized junctions	$11,065	145,000
30	Straight crossing paths at non-signalized junctions	$9,151	103,000
31	Vehicle(s) turning at non-signalized junctions	$8	1,000
32	Evasive action with prior vehicle maneuver	$177	3,000
33	Evasive action without prior vehicle maneuver	$106	3,000
34	Non-collision incident	$174	2,000
35	Object crash with prior vehicle maneuver	$1,413	23,000
36	Object crash without prior vehicle maneuver	$5	1,000
37	Other	$5,423	81,000
	Totals	***$ 169,011***	***2,318,000***

Table 4.6: Annual economic costs and comprehensive costs in all pre-crash scenarios (based on 2013 GES crash records)

No.	Pre-Crash Scenario	**Economic Costs** ($M, 2013 Dollars)	**Comprehensive Costs** ($M, 2013 Dollars)
1	Vehicle failure	$1,585	$6,567
2	Control loss with prior vehicle action	$14,425	$70,886
3	Control loss without prior vehicle action	$7,570	$28,833
4	Running red light	$1,193	$4,070
5	Running stop sign	$1,957	$8,564
6	Road edge departure with prior vehicle maneuver	$13,419	$64,545
7	Road edge departure without prior vehicle maneuver	$667	$1,693
8	Road edge departure while backing up	$27	$91
9	Animal crash with prior vehicle maneuver	$3,359	$9,651
10	Animal crash without prior vehicle maneuver	$2,652	$14,567
11	Pedestrian crash with prior vehicle maneuver	$5,086	$28,778
12	Pedestrian crash without prior vehicle maneuver	$925	$3,857
13	Pedalcyclist crash with prior vehicle maneuver	$1,221	$5,666
14	Pedalcyclist crash without prior vehicle maneuver	$2,094	$5,502
15	Backing up into another vehicle	$2,982	$10,873
16	Vehicle(s) turning – same direction	$550	$1,795
17	Vehicle(s) changing lanes – same direction	$6,948	$20,366
18	Vehicle(s) drifting – same direction	$5,222	$14,640
19	Vehicle(s) parking – same direction	$951	$5,926
20	Vehicle(s) making a maneuver – opposite direction	$6,086	$30,212
21	Vehicle(s) not making a maneuver – opposite direction	$121	$529
22	Following vehicle making a maneuver	$2,495	$8,702
23	Lead vehicle accelerating	$32,401	$1,184
24	Lead vehicle moving at lower constant speed	$6,319	$35,745
25	Lead vehicle decelerating	$7,167	$47,237
26	Lead vehicle stopped	$8,172	$91,009
27	LTAP/OD at signalized junctions	$883	$2,296
28	Vehicle turning right at signalized junctions	$5,102	$19,310
29	LTAP/OD at non-signalized junctions	$11,065	$41,088
30	Straight crossing paths at non-signalized junctions	$9,151	$31,012
31	Vehicle(s) turning at non-signalized junctions	$8	$24
32	Evasive action with prior vehicle maneuver	$177	$666
33	Evasive action without prior vehicle maneuver	$106	$556
34	Non-collision incident	$173	$500
35	Object crash with prior vehicle maneuver	$1,413	$6,026
36	Object crash without prior vehicle maneuver	$4	$9
37	Other	$5,423	$21,879
	Totals	***$169 billion***	***$645 billion***

Table 4.7: Annual economic cost and functional-years lost savings estimates from safety benefits of CAV technologies under the conservative effectiveness scenario (based on 2013 GES crash records)

No.	Combination of Safety Applications	Pre-Crash Scenario	Economic Costs Saved ($1M in 2013USD)	Saved Functional-years Lost (Years)
1	FCW & CACC	Following vehicle making a maneuver Lead vehicle accelerating Lead vehicle moving at lower constant speed Lead vehicle decelerating Lead vehicle stopped	$54,890	497,100
2	CICAS	Running red light Running stop sign LTAP/OD at signalized junctions Vehicle turning right at signalized junctions LTAP/OD at non-signalized junctions Straight crossing paths at non-signalized junctions Vehicle(s) turning at non-signalized junctions	$25,206	241,900
3	CLW	Vehicle failure Control loss with prior vehicle action Control loss without prior vehicle action	$16,300	208,200
4	RDCW & LKA	Road edge departure with prior vehicle Maneuver Road edge departure without prior vehicle maneuver Road edge departure while backing up	$9,468	104,300
5	SPVS	Vehicle(s) parking – same direction	$6,649	47,100
6	BSW & LCW	Vehicle(s) turning – same direction Vehicle(s) changing lanes – same direction Vehicle(s) drifting – same direction	$6,407	58,600
7	DNPW	Vehicle(s) making a maneuver – opposite direction Vehicle(s) not making a maneuver – opposite direction	$5,042	82,700
8	AEB & ESC	Animal crash with prior vehicle maneuver Animal crash without prior vehicle maneuver Evasive action with prior vehicle maneuver Evasive action without prior vehicle maneuver Object crash with prior vehicle maneuver Object crash without prior vehicle maneuver	$4,049	47,400
9	V2P	Pedestrian rash with prior vehicle maneuver Pedestrian crash without prior vehicle maneuver	$3,043	64,700
10	BCI	Backing up into another vehicle	$2,678	29,300
11	V2Ped	Pedalcyclist crash with prior vehicle maneuver Pedalcyclist crash without prior vehicle maneuver	$1,950	17,100
12	Combined Impacts of Safety Applications	Other	$1,628	24,200
	Totals		***$126,838***	***1,422,600***

Table 4.8: Annual economic cost and functional-years lost savings estimates from safety benefits of CAV technologies under the moderate effectiveness scenario (based on 2013 GES crash records)

No.	Combination of Safety Applications	Pre-Crash Scenario	Economic Costs Saved ($1M in 2013USD)	Saved Functional-years Lost (Years)
1	FCW & CACC	Following vehicle making a maneuver Lead vehicle accelerating Lead vehicle moving at lower constant speed Lead vehicle decelerating Lead vehicle stopped	$54,890	533,500
2	CICAS	Running red light Running stop sign LTAP/OD at signalized junctions Vehicle turning right at signalized junctions LTAP/OD at non-signalized junctions Straight crossing paths at non-signalized junctions Vehicle(s) turning at non-signalized junctions	$25,206	275,600
3	CLW	Vehicle failure Control loss with prior vehicle action Control loss without prior vehicle action	$16,300	250,900
4	RDCW & LKA	Road edge departure with prior vehicle Maneuver Road edge departure without prior vehicle maneuver Road edge departure while backing up	$9,468	157,800
5	SPVS	Vehicle(s) parking – same direction	$6,649	51,800
6	BSW & LCW	Vehicle(s) turning – same direction Vehicle(s) changing lanes – same direction Vehicle(s) drifting – same direction	$6,407	64,000
7	DNPW	Vehicle(s) making a maneuver – opposite direction Vehicle(s) not making a maneuver – opposite direction	$5,042	94,900
8	AEB & ESC	Animal crash with prior vehicle maneuver Animal crash without prior vehicle maneuver Evasive action with prior vehicle maneuver Evasive action without prior vehicle maneuver Object crash with prior vehicle maneuver Object crash without prior vehicle maneuver	$4,836	59,500
9	V2P	Pedestrian rash with prior vehicle maneuver Pedestrian crash without prior vehicle maneuver	$3,649	78,700
10	BCI	Backing up into another vehicle	$2,792	32,300
11	V2Ped	Pedalcyclist crash with prior vehicle maneuver Pedalcyclist crash without prior vehicle maneuver	$2,289	21,000
12	Combined Impacts of Safety Applications	Other	$2,170	32,200
	Totals		***$139,694***	***1,652,200***

Table 4.9: Annual economic cost and functional-years lost savings estimates from safety benefits of CAV technologies under the aggressive effectiveness scenario (based on 2013 GES crash records)

No.	Combination of Safety Applications	Pre-Crash Scenario	Economic Costs Saved ($1M in 2013USD)	Saved Functional-years Lost (yrs)
1	FCW & CACC	Following vehicle making a maneuver Lead vehicle accelerating Lead vehicle moving at lower constant speed Lead vehicle decelerating Lead vehicle stopped	$54,890	557,200
2	CICAS	Running red light Running stop sign LTAP/OD at signalized junctions Vehicle turning right at signalized junctions LTAP/OD at non-signalized junctions Straight crossing paths at non-signalized junctions Vehicle(s) turning at non-signalized junctions	$25,206	326,500
3	CLW	Vehicle failure Control loss with prior vehicle action Control loss without prior vehicle action	$16,300	293,500
4	RDCW & LKA	Road edge departure with prior vehicle Maneuver Road edge departure without prior vehicle maneuver Road edge departure while backing up	$9,468	210,300
5	SPVS	Vehicle(s) parking – same direction	$6,649	55,400
6	BSW & LCW	Vehicle(s) turning – same direction Vehicle(s) changing lanes – same direction Vehicle(s) drifting – same direction	$6,407	68,600
7	DNPW	Vehicle(s) making a maneuver – opposite direction Vehicle(s) not making a maneuver – opposite direction	$5,042	106,300
8	AEB & ESC	Animal crash with prior vehicle maneuver Animal crash without prior vehicle maneuver Evasive action with prior vehicle maneuver Evasive action without prior vehicle maneuver Object crash with prior vehicle maneuver Object crash without prior vehicle maneuver	$5,622	59,500
9	V2P	Pedestrian rash with prior vehicle maneuver Pedestrian crash without prior vehicle maneuver	$4,254	78,700
10	BCI	Backing up into another vehicle	$2,892	32,300
11	V2Ped	Pedalcyclist crash with prior vehicle maneuver Pedalcyclist crash without prior vehicle maneuver	$2,627	21,000
12	Combined Impacts of Safety Applications	Other	$2,712	40,300
	Totals		***$151,046***	***1,882,300***

4.4 Microsimulation of AVs in the Traffic System

Section 4.5 introduces Vissim, the microsimulation software chosen for this project, and explains the car-following model Vissim implements represent human driver behavior. In order to model both the HVs and AVs together, and produce working data, new driver models were created to run in place of Vissim's existing driver model. The following sub-sections explain this process in greater detail, and the results and discussion begin in Section 4.6.

4.4.1 Background to Car-Following Model

In order to understand the ramifications of introducing AVs into the traffic system, we created a microsimulation model that would approximate the decision processes of AVs and then estimated the number of collisions that would occur given different rates of AV market penetration.

We employed the modeling software Vissim, which is a flexible modeling environment enabling us to implement our own AV driver module through the software's External Driver Module. An explanation of the logic Vissim employs for its car-following model is outlined in Section 4.4.2, our modifications to that car-following logic to model AVs are found in Section 4.4.3, and finally our implementation of that logic is found in Section 4.4.4.

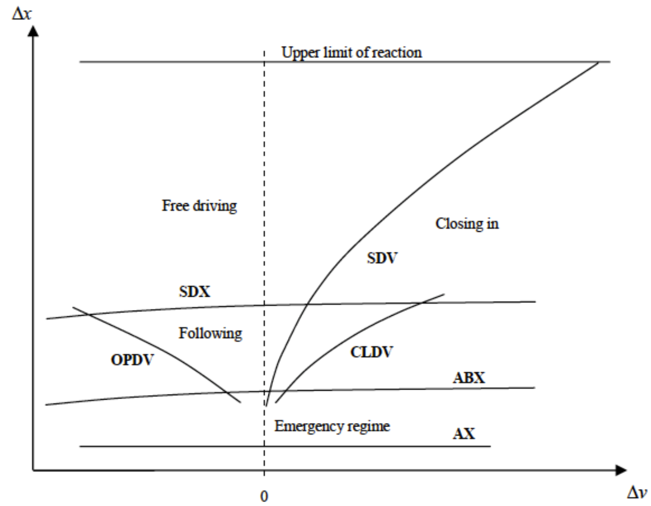
It is currently impossible to directly assess the impacts of AVs on the safety of a traffic system, primarily because AVs do not yet exist on public roadways, except for a few isolated examples. However, one of the outputs from Vissim is a complete list of the locations and velocities of all vehicles at all times. This information is inserted into SSAM, which was released by the FHWA to help analyze potential conflicts between vehicles. Because Vissim does not explicitly model crashes, SSAM uses other factors—minimum time-to-collision, minimum post-encroachment, initial deceleration rate, maximum deceleration rate, maximum speed, maximum speed differential, classification of potential collisions into either lane-change, rear-end, or path-crossing events, and vehicle velocity change had the event proceeded to a crash—as surrogates to determine whether a collision might occur.

Because there are many, many more conflicts than crashes, it was possible to develop an equation to show how the number of conflicts per hour can serve as a surrogate for the number of crashes per year. The FHWA reports this relationship as:

$$\frac{Crashes}{Year} = 0.119 * \left(\frac{Conflicts}{Hour}\right)^{1.419}$$

4.4.2 The Car-Following Model

Vissim models traffic flow using a psycho-physical car-following model, which attempts to account for the inherent randomness of drivers' preferences and tolerances for risk. Vissim's model is based on two papers by Wiedemann (1974 & 1991). Wiedemann proposes that drivers follow four different "regimes" that govern their behavior: free driving, following, closing, and emergency. These regimes can be seen as a function of differences in distance and velocity in Figure 4.1.



Source: Olstam & Tapani, 2004

Figure 4.1: Thresholds of the Wiedemann car-following model

In free driving, the driver perceives that no vehicles are in a position to interfere with her choices. Thus, the driver is able accelerate to her preferred cruising speed at her preferred acceleration rate and is constrained only by the geometric and service characteristics of the road. However, although there are no external objects that mandate a speed change from the driver, Vissim will nonetheless allow her speed to oscillate around her preferred cruising speed to replicate random effects from imprecise throttle control and other minor sources of mechanical error.

In the following regime, the driver attempts to maintain a safe distance between herself and the vehicle in front and a minimal difference in speed. This distance depends upon the driver's speed; e.g., since it takes a longer distance to safely stop at higher speeds, the following regime will dictate that drivers will maintain larger following distances on an interstate than on a local road. At all times, vehicles will maintain a minimum distance between themselves and the next vehicle. This reflects the distance between vehicles that is present even when all vehicles are stopped at a traffic control signal or in gridlock. Like the free driving regime, Vissim will allow drivers to vary their following distance to model the variability in control and tolerance that different drivers possess.

The closing regime joins the free driving and following regimes. It marks the period when the driver recognizes that her speed is greater than that of the next vehicle, but before she has reached the minimum safe following distance. In this regime, the driver begins to decrease her speed, aiming to achieve a delta-v of 0 relative to the vehicle she is following at the minimum safe distance. Vissim replicates real driver behavior by randomizing the perception and reaction times of drivers. The final regime, the emergency regime, occurs when the delta-v of the vehicles is so great that the minimum following distance mentioned in the following regime might be violated. In this regime, the driver will apply a maximal braking force in the attempt to avoid a collision (although Vissim does not have a protocol for simulating crashes). This regime does not contain any terms intended to create a random distribution.

Almost all car-following behavior is governed by cycles of the first three regimes. Vehicles are alone on a road in free-driving, then switch to the closing regime as they approach vehicles stopped at a control signal and decelerate to a stop. As the queue starts up when the signal changes, the driver oscillates between free driving (as the next vehicle accelerates away), following (as the driver matches speeds), and even the closing regime (if the driver misjudges the next vehicle's velocity). Vissim (like most drivers) will go to great lengths to avoid vehicles needing to implement the emergency regime.

4.4.3 Model Modifications

The simulation of AVs within Vissim required a number of assumptions. When Vissim models human drivers using the Wiedemann equations, it allows a number of parameters to vary around a random normal distribution that are built into the equations. This allows the simulator to more accurately model the preferences that different drivers have for their following distances, aggression in acceleration or deceleration, and their ability to perceive the speed of other vehicles.

Traffic microsimulators such as Vissim attempt to predict the steady-state traffic conditions that will persist along a corridor or throughout an area despite the very real variability that is found between drivers and vehicles and the potentially large effects randomness that permeate such systems in real life. Vissim captures these effects through several stochastic variables that are assigned individually to each vehicle as it enters the simulator. Varying normally, these variables allow the simulator to more accurately model the preferences that different drivers have for their following distances, aggression in acceleration or deceleration, and their ability to perceive the speed of other vehicles.

When AVs are deployed in the real world, their behavior may also be stochastic in some of the same ways as human drivers. Sensing errors and mechanical imprecision mean that AVs will have some of the same problems maintaining a constant speed or following distance as human drivers; however, there are no good estimates for the magnitudes of these errors. Lacking any information on these magnitudes, we chose to set the variance of the *driver* random terms to zero and to leave the *vehicle* random terms at the values normally set by Vissim. (The randomly distributed terms in the model have a mean of 0.5 so they cannot be eliminated entirely.)

Other parameters, including the minimum acceptable gap for merging or turning, sight distance, and lane change preferences where set at the upper bounds suggested by Olstam & Tapani (2004). These upper bounds represent the most conservative driving behaviors and these behavior parameters are a reasonable first guess at AV driver behavior because car manufacturers, recognizing their potential liability, will almost certainly not make their vehicles aggressive in any way. Indeed, many self-driving cars being tested on the road today will come to a complete stop if they experience significant sensory uncertainty. By placing the parameter values at the conservative end of the normal human range for the current Vissim model we assume that these kinds of conflicts have been systematically resolved.

These assumptions would lead one to expect that AVs will be more cautious than human drivers. As just a few examples, AVs are more willing to wait in a queue rather than to aggressively merge into a neighboring lane. AVs accelerate from a stop more slowly in order to increase ride comfort and will begin to decelerate at a farther distance than human drivers.

When AVs are deployed in the real world, their behavior may also be stochastic in some of the same ways as human drivers. Sensing errors and mechanical imprecision mean that AVs will have some of the same problems maintaining a constant speed or following distance as human drivers; however, there are no good estimates for the magnitudes of these errors. Lacking any information on these magnitudes, we chose to set the variance of the random terms to zero. (The randomly distributed terms in the model have a mean of 0.5 so they cannot be eliminated entirely.) All of the other parameters are set to the values suggested by Olstam & Tapani (2004).

4.4.4 Implementation of the Model in Vissim

To implement the Wiedemann equations in Vissim, we wrote two External Driver Models (EDMs). The EDM is a .dll file that replaces the built-in Vissim driver models with a user-specified behavior. One of the EDMs observed the Wiedemann equations with 0 variance of random terms (to model AVs) and the other EDM observed all of the Wiedemann equations, including the random terms (to model human drivers). Because so much of the way Vissim implements the Wiedemann model in its internal driver models is proprietary information, we felt that the only fair comparison we could make for the AV EDM was to implement a human driver model that took into account all of the same factors. This would mean that we were not testing whether our essentially un-calibrated model was less safe than the best model of human behavior that the PTV Group's Vissim can produce.

4.5 Vissim Network Design

The team designed six networks in Vissim to produce trajectory data for different scenarios. The trajectory output data was analyzed in SSAM to understand how AVs might affect potential conflicts and other safety parameters from HVs. Various scenarios were designed to analyze the safety of AVs under different conditions, including traffic, volume, and the number of lanes. This section will review each network separately, providing an introduction to the design and capacities used.

4.5.1 Four-Way Intersection

The four-way intersection network was designed with two, one-way single-lane roads that intersect at a four-way stop (Figure 4.2). The main purpose of this network was to determine how accurately AVs can be modeled for such an environment. The red and green area in the middle of the intersection indicates conflict zones; green is right-of-way (ROW), and red indicates a yield. After doing several runs on this network, it was observed that vehicles do not observe stop signs, signals, or ROWs under the EDMs created for these simulations. Therefore, with the current EDMs' signalized intersections and any networks requiring the use of ROWs cannot be properly modeled. To attempt to adjust for this characteristic, vehicle inputs were kept low enough to prevent any congestion. This will be explored in greater detail in the SSAM section.

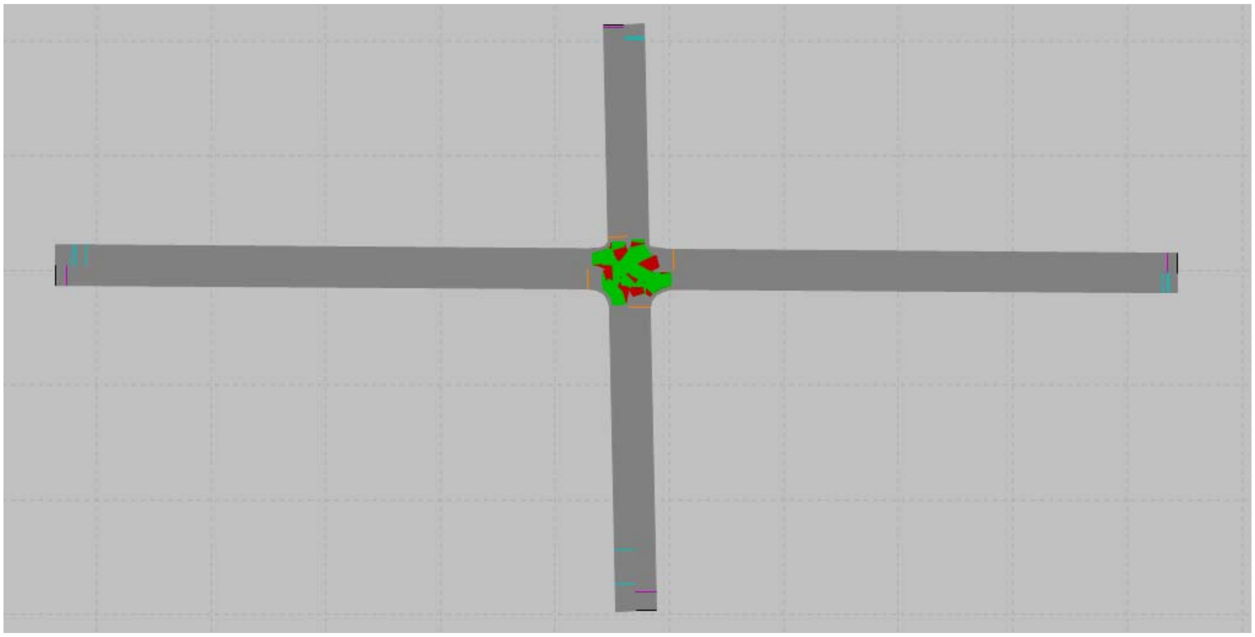


Figure 4.2: Four-way intersection network

4.5.2 Bottleneck-Urban Roadway

Bottlenecks form when there is a reduction in the number of lanes on a roadway (as Figure 4.3 depicts), and are often areas of congestion, which leads to delays and potential conflicts. The length of the merge lanes can also impact congestion; however, this component was not explored during these simulations.

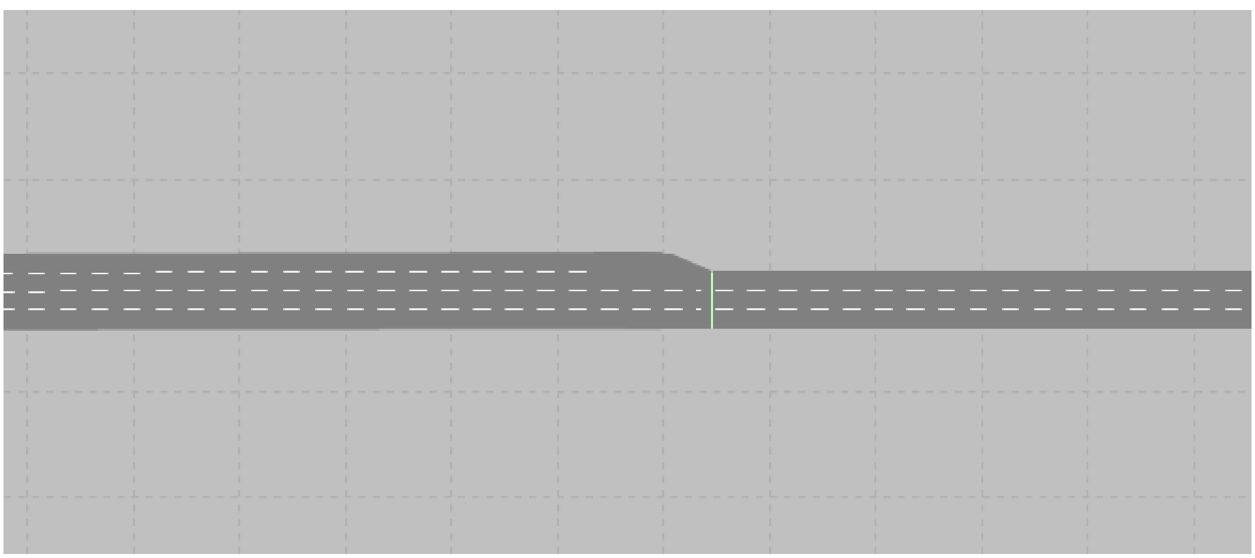


Figure 4.3: Bottleneck example in urban roadway network

4.5.3 On-Ramp/Off-Ramp Freeway

The on-ramp/off-ramp freeway models a feeder road with an on-ramp and an off-ramp shortly down road. The input volume was kept low on the feeder road, to prevent unrealistic conflicts at the conflict zones, indicated by the red and green areas in Figure 4.4, since the EDMs do not observe these yields.

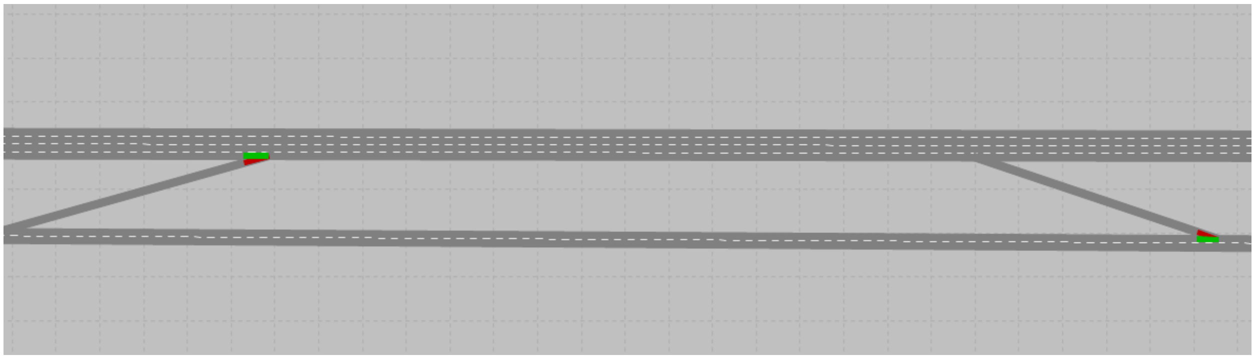


Figure 4.4: Freeway on ramp and off ramp

Intersection of IH 35 and Wells Branch Parkway

The intersection of IH 35 and Wells Branch Parkway in Austin was selected to be analyzed for various concentrations of AVs (Figure 4.5). This network intersection is on a signalized network. The traffic volume at this intersection is high and was therefore a good candidate to provide a realistic conflict zone for vehicles. Using this intersection, a network model was created in Vissim. The primary purpose of the intersection network was to determine how AVs would behave in such an environment.

After conducting several Vissim runs on this network, it was observed that congestion is lower when the traffic mix includes AVs. Also, the number of conflicts decreases with increasing AV concentration.

Figure 4.5: IH 35 and Wells Branch Parkway

Intersection of IH 35 and 4th Street

The intersection at IH 35 and 4th street in Austin is an intersection where the traffic volume is moderate (Figure 4.6). This network has four one-way double-lane roads that intersect at two stop signs. The primary purpose of the intersection network was to determine how AVs would behave at such an environment. Using this intersection, a network model was created in Vissim. Various scenarios were accordingly constructed to simulate different traffic conditions.

After conducting several Vissim runs on this network, it was observed that congestion is lower in case of AVs. Additionally, the number of conflicts decreases with the increase in the concentration of AVs in the vehicle traffic at this specific intersection network.

Figure 4.6: IH 35 and 4th Street

Intersection of Manor Road and E M Franklin Avenue

A network was designed around the intersection at Manor Road and E M Franklin Avenue in Austin (Figure 4.7). The traffic volume at this intersection is expected to be low. This network has three one-way double-lane roads that intersect at two stop signs. The primary purpose of the intersection network was to determine how AVs would behave at such an environment. Using this intersection, a network model was created in Vissim. Various scenarios were subsequently constructed to simulate different traffic conditions.

After performing several runs on this network, results similar to those of intersections were observed. It was observed that congestion is lower in case of AVs. Also, the number of conflicts decreases with the increase in the concentration of AVs in the vehicle traffic at this specific intersection network.

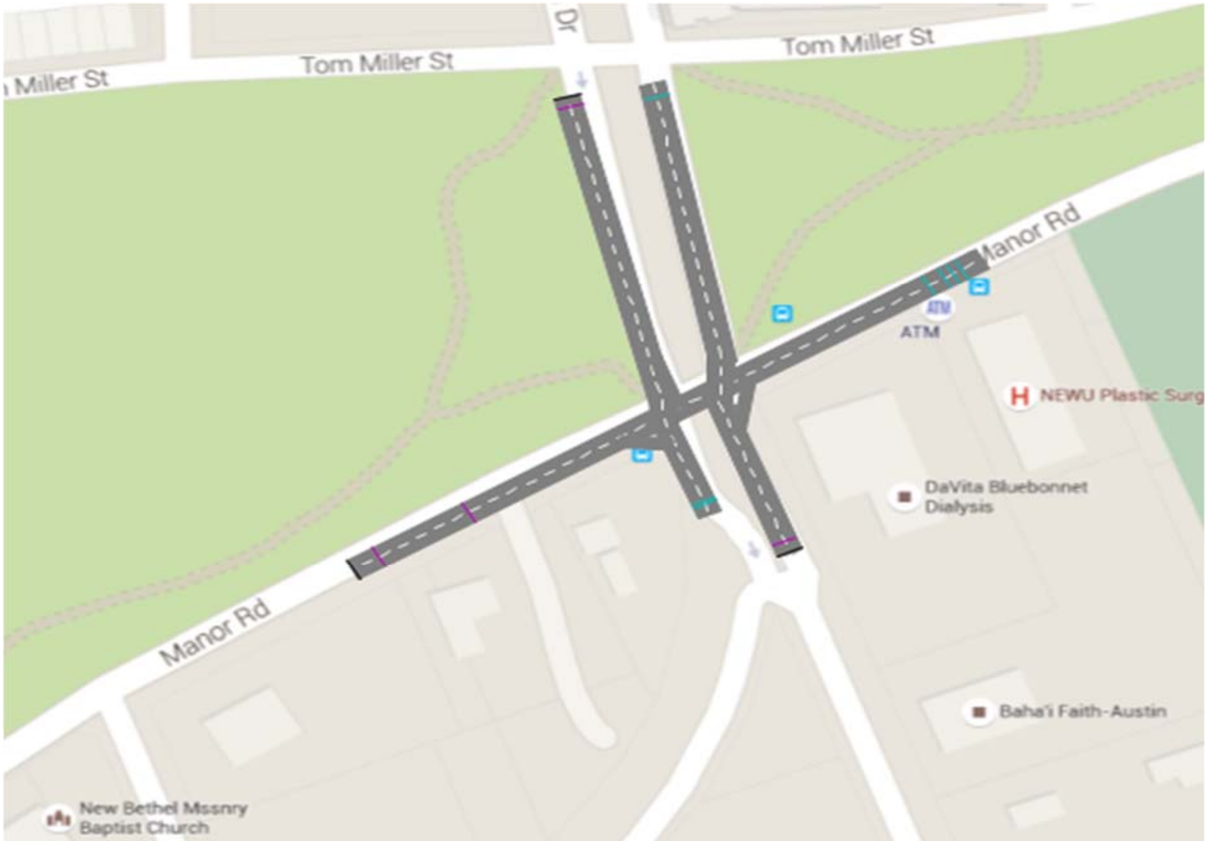


Figure 4.7: Manor Road and E M Franklin Avenue

4.5.4 Simulations in Vissim

Each network ran 10 simulations for 3,600 simulation seconds. By gathering trajectory data for one simulation hour, the number of potential crashes per year can be calculated by using the output data from SSAM, based on the equation from the USDOT in Section 4.4.1.

Each network ran ten times for 1 hour of simulation using the HV EDM only, and then varying percentages of AVs and HVs were run together, ten times per each flow. These varying percentages of AV volume included 25%, 50%, 75%, and 100%. At the 100% AV flow, the AV EDM was used without the HV EDM. The bottleneck urban roadway network was created with three different flows per hour —low at 500 vehicles, medium at 1000 vehicles, and high at 3000 vehicles—to see whether capacity altered the relationship of conflicts between the HV EDM and AV EDM. Due to the small scale of the networks tested, capacity was kept low enough, even at high flows, to prevent a build-up of vehicles (bumper-to-bumper traffic). When test simulations ran such high volumes of vehicles, the resulting trajectory data always generated abnormally high, unrealistic conflict numbers in SSAM that went up into the tens of thousands range. Therefore, capacity for these networks prohibited volume to reasonable levels.

The other two networks, four-way intersection and on-ramp/off-ramp freeway, were only run with a single volume input for all simulations. The four-way intersection had a volume of 70 vehicles for northbound/southbound lanes, and 50 vehicles for eastbound/westbound lanes; while the on-ramp/off-ramp network had a volume of 1,000 vehicles for the freeway and 100 for the feeder road. During the simulation for the four-way intersection, it was observed that the EDMs do not follow stop signs or conflicts areas. Therefore, some assumptions were made when analyzing the SSAM data in order to draw reasonable conclusions about results. This will be explained in more detail in Section 4.6.

4.6 SSAM Analysis Output

4.6.1 Introduction and Definitions

SSAM analyzes trajectory data, in the form of a ".trj" file from simulation software, such as Vissim, and identifies conflicts. Conflicts are defined as situation in which two vehicles will collide unless action is taken, and are categorized into Unclassified, Crossing, Rear End, and Lane Change. For each conflict identified, there are several surrogate safety measures that include the following:

- Minimum time-to-collision (TTC).
- Minimum post-encroachment time (PET).
- Initial deceleration rate (DR).
- Maximum deceleration rate (MaxD).
- Maximum speed (MaxS).
- Maximum speed differential (DeltaS).
- Vehicle velocity change had the event proceeded to a crash (DeltaV).

Table 4.10: SSAM measures and definitions

SSAM Measure	Definitions
TTC	The minimum time-to-collision value observed during the conflict. This estimate is based on the current location, speed, and trajectory of two vehicles at a given instant.
PET	The minimum post encroachment time observed during the conflict. Post encroachment time is the time between when the first vehicle last occupied a position and the second vehicle subsequently arrived at the same position. A value of 0 indicates an actual collision.
MaxS	The maximum speed of either vehicle throughout the conflict (i.e., while the TTC is less than the specified threshold). This value is expressed in feet per second or meters per second, depending on the units specified in the corresponding trajectory file.
DeltaS	The difference in vehicle speeds as observed at **tMinTTC**. More precisely, this value is mathematically defined as the magnitude of the difference in vehicle velocities (or trajectories), such that if ***v1*** and ***v2*** are the velocity vectors of the first and second vehicles respectively, then **DeltaS = || *v1* – *v2* ||**. Consider an example where both vehicles are traveling at the same speed, ***v***. If they are traveling in the same direction, **DeltaS** = 0.
DR	The initial deceleration rate of the second vehicle. Note that in actuality, this value is recorded as the instantaneous acceleration rate. If the vehicle brakes (i.e., reacts), this is the first negative acceleration value observed during the conflict. If the vehicle does not brake, this is the lowest acceleration value observed during the conflict. This value is expressed in feet per second or meters per second, depending on the units specified in the corresponding trajectory file.
MaxD	The maximum deceleration of the second vehicle. Note that in actuality, this value is recorded as the minimum instantaneous acceleration rate observed during the conflict. A negative value indicates deceleration (braking or release of gas pedal). A positive value indicates that the vehicle did not decelerate during the conflict. This value is expressed in feet per second or meters per second, depending on the units specified in the corresponding trajectory file.
MaxDeltaV	The maximum **DeltaV** value of either vehicle in the conflict. This is a surrogate for the severity of the conflict, calculated assuming a *hypothetical* collision of the two vehicles in the conflict.

The surrogate measures focused on here are Max S, MaxDelta V, and MaxD—Max S and MaxDeltaV because they are related to severity of a potential collision, and MaxD because it represents how well, on average, vehicles avoided collisions. From the SSAM Manual, TTC and PET are meant to indicate likelihood of a conflict, as PET = 0 indicates an actual collision, but they were not included in this analysis because of the nature of the EDMs. The vehicles are already following quite close to each other, producing lower TTC and PET values, which inflate the number of conflicts recognized by SSAM. Therefore, for driver models used in Vissim, TTC and PET do not give a good indication of the likelihood of a collision.

4.6.2 Urban Roadway Bottlenecks

Table 4.11 shows the results of bottleneck conflicts disaggregated by type. Table 4.12 summarizes the percent decrease in total number of conflicts between 100% HVs, and 100% AVs, for low, medium, and high flows (see Figures 4.8 through 4.10 for a plot of every conflict type at their respective flows).

Table 4.11: Bottleneck conflict results disaggregated by type

	Percent Flow	Total	Unclassified	Crossing	Rear End	Lane Change
Low	100% HU	5	0	0	5	0
	25% AV	9	0	0	9	0
	50% AV	7	0	0	7	0
	75% AV	4	0	0	4	0
	100% AV	3	0	0	3	0
Medium	100% HU	137	0	0	125	12
	25% AV	115	0	0	106	9
	50% AV	85	0	0	79	6
	75% AV	50	0	0	42	8
	100% AV	17	0	0	8	9
High	100% HU	1972	0	0	1547	425
	25% AV	1741	0	1	1307	433
	50% AV	1393	0	0	915	478
	75% AV	1064	0	0	608	456
	100% AV	684	0	0	256	428

Table 4.12: Percent difference in conflicts between HVs and AVs

	Percent decrease between 100% HU and 100 % AV
Low	40
Medium	88
High	65

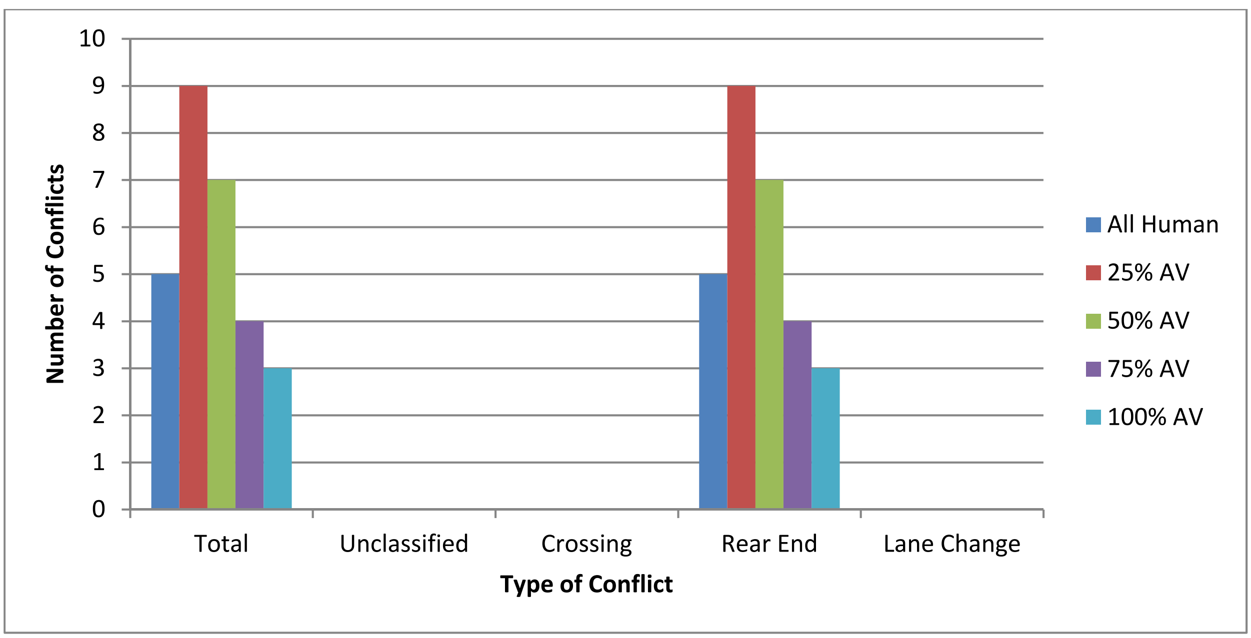


Figure 4.8: Low-flow conflicts disaggregated by type

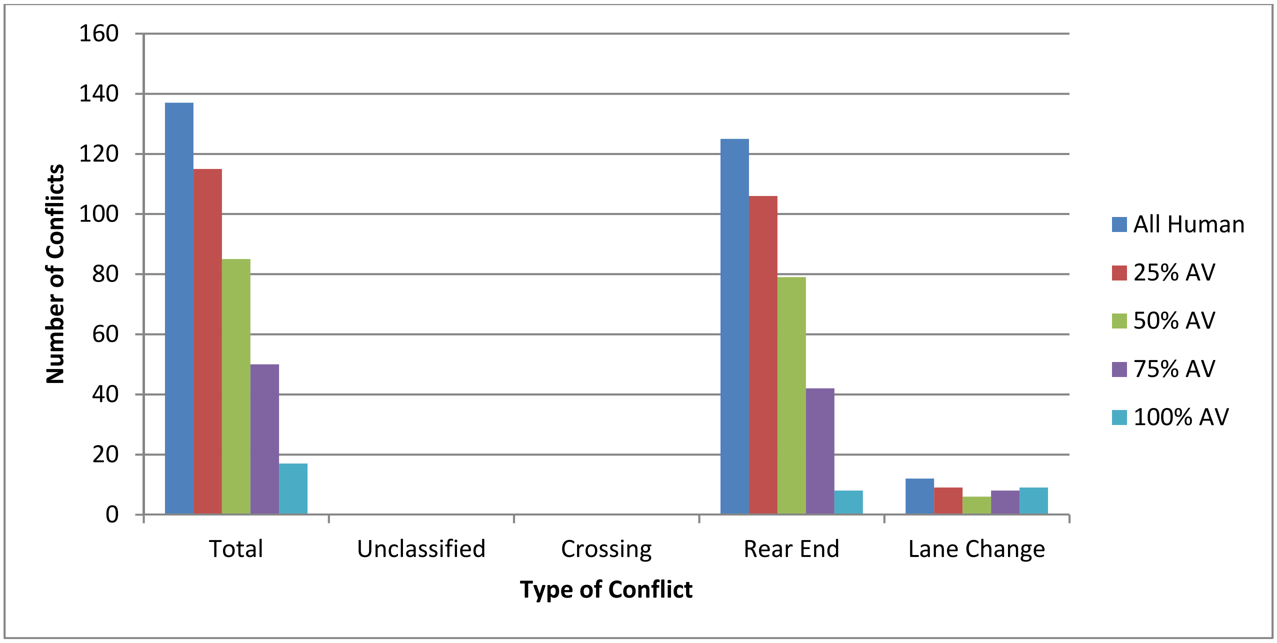


Figure 4.9: Medium-flow conflicts disaggregated by type

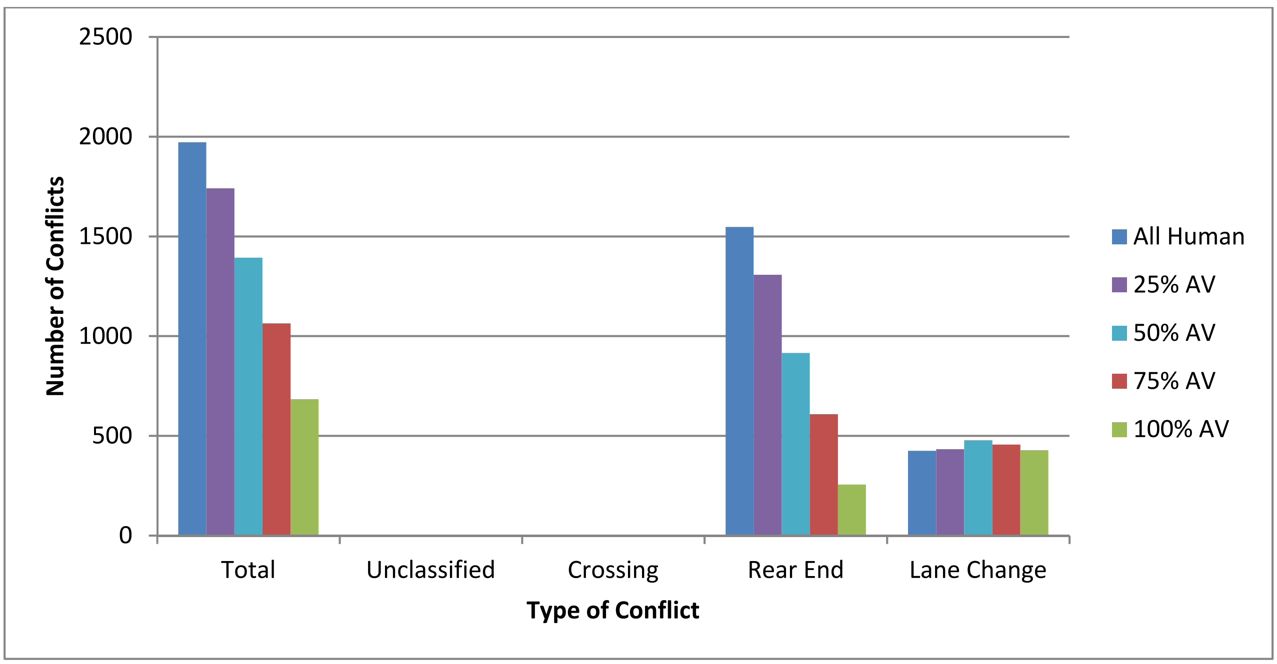


Figure 4.10: High-flow conflicts disaggregated by type

At low flow, the MaxDeltaV values are greater than HVs with 25 and 50% AVs, but then decrease for the 75 and 100% AVs. At medium and high flow, the values are lower for all AV percentages, but only noticeably for 100% AVs. MaxS also decreases significantly between 100% HU and 75% AV/100% AV for all flow volumes. For example, at medium flow, the MaxS for all HVs is 29.09 m/s, while at 100% AVs it is 14.84 m/s, which is almost a 50% decrease. Table 4.13

displays the surrogate safety measures from the SSAM output, and Table 4.14 summarizes the percent differences between the HV and AV EDMs.

Table 4.13: Bottleneck surrogate safety measures

	Mean Value	100% HU	25% AV	50% AV	75% AV	100% AV
Low	MaxS	25.56	29.38	27.55	20.72	16.52
	MaxDeltaV	3.96	5	4.71	3.62	2.53
	MaxD	-4.66	-5.49	-5.15	-1.76	-0.27
Medium	MaxS	29.09	29.18	27.61	25.51	14.84
	MaxDeltaV	5.18	5.13	4.5	4.5	2.54
	MaxD	-6.3	-6.2	-5.94	-6.09	-3.52
High	MaxS	20.92	20.24	18.83	17.47	14.7
	MaxDeltaV	4.71	4.69	4.14	3.83	2.98
	MaxD	-5.5	-5.56	-5.32	-4.96	-4.62

Table 4.14: Percent differences in safety measures between HVs and AVs (bottleneck)

Percent Difference		25% AV	50% AV	75% AV	100% AV
Low	MaxS	15	8	-19	-35
	MaxDeltaV	26	19	-9	-36
	MaxD	18	11	-62	-94
Medium	MaxS	0	-5	-12	-49
	MaxDeltaV	-1	-13	-13	-51
	MaxD	-2	-6	-3	-44
High	MaxS	-3	-10	-16	-30
	MaxDeltaV	0	-12	-19	-37
	MaxD	1	-3	-10	-16

This data indicates that AVs are safer than HVs in a bottleneck situation, especially as the percentage of AVs increases. At 50% AVs, the data only agrees at medium and high flows, and at only 25% AVs the data provides mixed results. More simulations on a variety of bottleneck networks will need to be run to draw concrete conclusions.

4.6.3 Four-way Intersections

Table 4.15 summarizes the total number of conflicts predicted by SSAM, for the four-way intersection simulation. The data does not correspond to expected trends, based on the results seen from the other simulations. There is no variation in the number of conflicts between the different percentages of AV flow. Figure 4.11 provides results for the four-way conflicts disaggregated by type and Table 4.16 graphs the four-way intersection surrogate safety measures.

Table 4.15: Four-way intersection conflicts disaggregated by type

Human External Driver Model and AV External Drive Model					
Summary	**Total**	**Unclassified**	**Crossing**	**Rear End**	**Lane Change**
100% HU	25	0	23	0	2
25% AV	25	0	23	0	2
50% AV	24	0	22	0	2
75% AV	24	0	22	0	2
100% AV	24	0	22	0	2

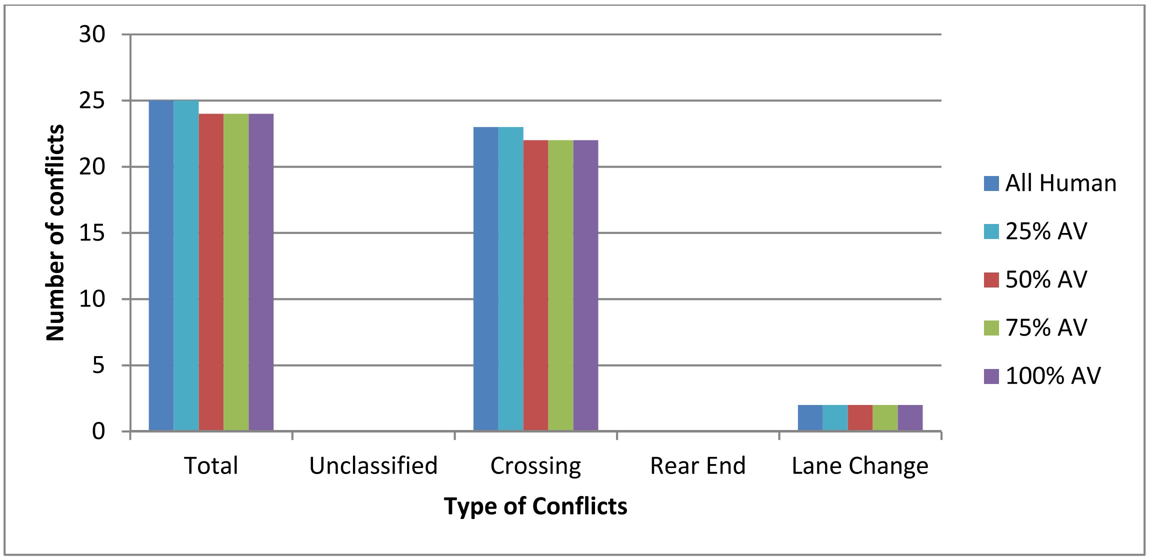


Figure 4.11: Four-way conflicts disaggregated by type

Table 4.16: Four-way intersection surrogate safety measures

Mean Values	100% HU	25% AV	50% AV	75% AV	100% AV
MaxS	19.95	20.01	19.97	20.12	20.12
MaxDeltaV	13.34	13.36	13.69	13.64	13.64
MaxD	0.65	0.72	0.6	1.02	1.02

The severity of crashes does not vary much between the HVs and the varying percentages of AVs. However, there is an increase in MaxD for the 75% and 100% AVs. From the definition in Table 4.10 in sub-section 4.7.1, MaxD is the maximum deceleration of the second vehicle, and when positive indicates that the vehicle did not decelerate during the conflict. The mean MaxD for every simulation run generated a positive value, meaning on average, the second vehicle involved in the conflict did not decelerate. Though this is an undesirable action in the EDMs, it corresponds to the observation in Vissim, when the vehicles did not observe stop signs or conflict zones. The majority of conflicts were the Crossing type, which is why the MaxD is positive. Thus, the conflicts types can largely be ignored. However, for any future simulations the EDMs will need to be adjusted in order to reasonably model AVs at intersections.

As it stands with current data (Table 4.17), the results are inconclusive for this network, as the number of conflicts remained constant for each run, regardless of percentage of AV flow. There was also a decrease in safety, in terms of deceleration time (MaxD), for the 75 and 100% AV inputs.

Table 4.17: Percent differences in safety measures between HVs and AVs (four-way)

Percent Difference	25% AV	50% AV	75% AV	100% AV
MaxS	0	0	1	1
MaxDeltaV	0	3	2	2
MaxD	11	-8	57	57

4.6.4 Freeway On-Ramps and Off-Ramps

For this network there was a slight increase of two conflicts during the 25% AV flow (Table 4.18); however, this is an anomaly among the other data sets. In general, Table 4.18 and Figure 4.13 show that as the percentage of AVs increases, the number of conflicts decreases, with the least number of conflicts occurring at 100% AVs. The most drastic decreases in conflicts occur with Rear End types. There was a slight decrease in the severity of crashes as the percentages of AVs increased, as well as a better deceleration response (Table 4.19). The results indicate that AVs decrease the number of conflicts for networks involving entrance and exit ramps onto or off of a freeway.

Table 4.18: On-ramp/off-ramp conflicts disaggregated by type

Human External Driver Model and AV External Drive Model					
Summary	**Total**	**Unclassified**	**Crossing**	**Rear End**	**Lane Change**
100% HU	117	0	0	96	21
25% AV	119	0	0	97	22
50% AV	85	0	0	70	15
75% AV	81	0	0	65	16
100% AV	60	0	0	46	14

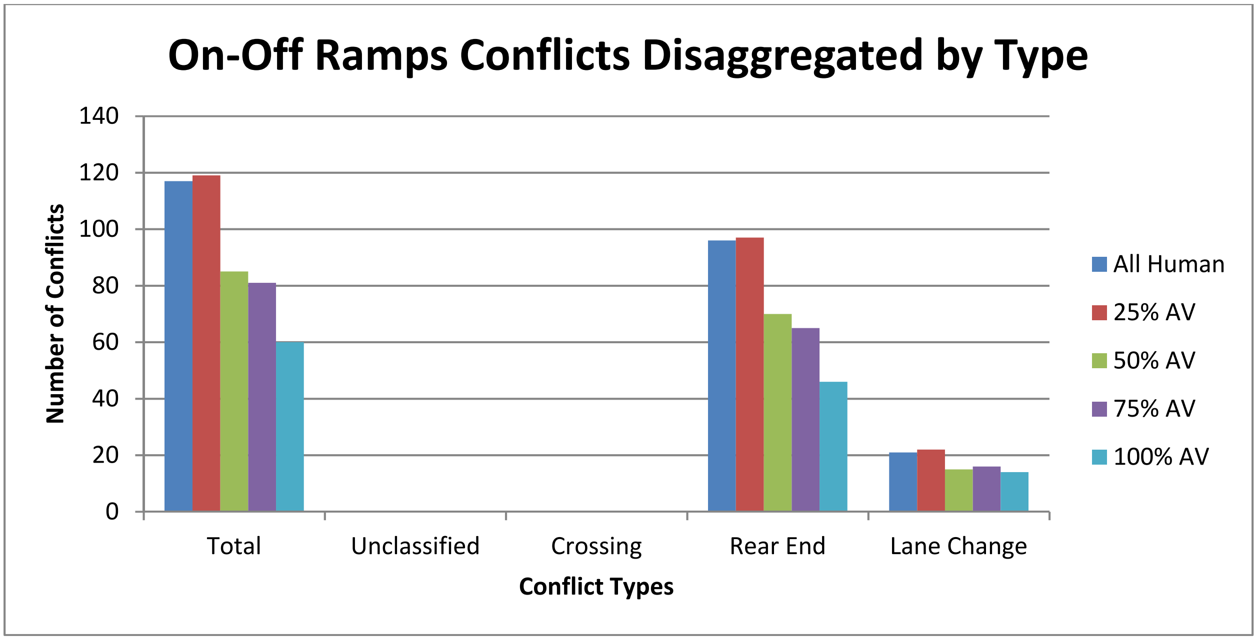


Figure 4.12: On-ramp/off-ramp conflicts disaggregated by type

Table 4.19: On-ramp/off-ramp surrogate safety measures

Mean Values	100% HU	25% AV	50% AV	75% AV	100% AV
MaxS	30.28	30.18	30.64	29.22	28.45
MaxDeltaV	4.07	4.32	4.41	3.71	3.23
MaxD	-3.72	-3.52	-3.51	-3.27	-2.66

4.6.5 Intersection of IH 35 and Wells Branch Parkway

The simulation results for network intersection of IH 35 and Wells Branch Parkway indicated that the number of conflicts comprehensively decreased with the addition of AVs. Figure 4.13 summarizes the total number of conflicts and other measures for the various scenarios predicted by SSAM.

At the specified flow, the MaxDeltaV and DeltaS values were found to decrease consistently with the increase in the concentration of AVs at this intersection. MaxS also decreases significantly between 100% HU and 50% AV/100% AV. For example, the MaxS for all HVs is 19.28 m/s, while at 100% AVs it is 17.87 m/s, which is almost an 8% decrease. Similarly, the DeltaS for all HVs is 17.21 m/s, while at 100% AVs it is 9.36 m/s, which is almost a 45% decrease. Finally, the MaXDeltaV for all HVs is 9.07 m/s, while at 100% AVs it is 4.94 m/s, which is almost a 45% decrease.

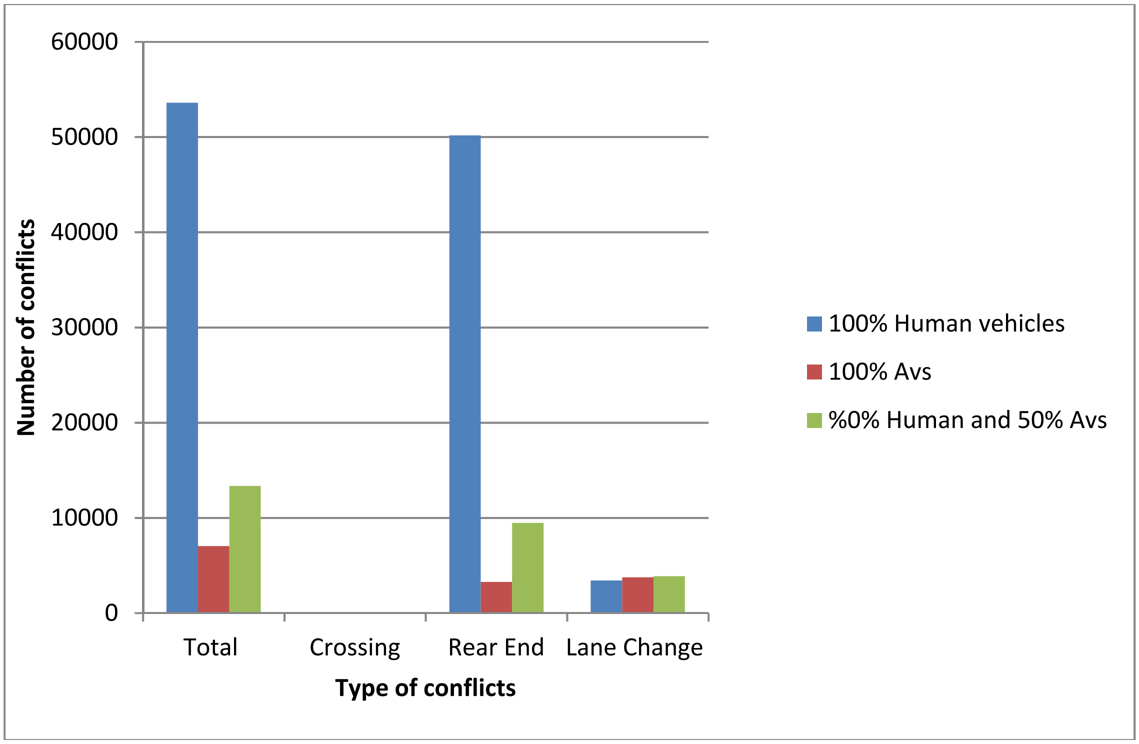


Figure 4.13: Intersection conflicts disaggregated by type

The following results were observed for 100% HVs at the intersection of IH 35 and Wells Branch Parkway (Table 4.20 and 4.21).

Table 4.20: Intersection of IH 35 and Wells Branch Parkway conflict summary

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	53605	0	0	50176	3429
Run 1	11440	0	0	11106	334
Run 2	2632	0	0	2262	370
Run 3	1617	0	0	1284	333
Run 4	1697	0	0	1292	405
Run 5	3350	0	0	2995	355
Run 6	1176	0	0	921	255
Run 7	1143	0	0	898	245
Run 8	27168	0	0	26719	449
Run 9	1576	0	0	1230	346
Run 10	1806	0	0	1469	337

Table 4.21: Intersection of IH 35 and Wells Branch Parkway surrogate safety measures

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.07	0.07
PET	0	3.8	0.04	0.04
MaxS	0	34.5	19.28	6.01
DeltaS	0	24.07	17.21	23.02
DR	-8.39	3	-3.92	7.05
MaxD	-8.44	3	-6.45	3.79
MaxDeltaV	0	13.71	9.07	6.51

Tables 4.22 and 4.23 show results observed for 100% AVs at the intersection of IH 35 and Wells Branch Parkway.

Table 4.22: Intersection of IH 35 and Wells Branch Parkway conflict summary

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	7035	0	3	3278	3754
Run 1	825	0	1	392	432
Run 2	787	0	0	356	431
Run 3	653	0	0	315	338
Run 4	749	0	0	365	384
Run 5	704	0	0	310	394
Run 6	783	0	1	376	406
Run 7	478	0	0	175	303
Run 8	563	0	0	251	312
Run 9	868	0	1	407	460
Run 10	625	0	0	331	294

Table 4.23: Intersection of IH 35 and Wells Branch Parkway surrogate safety measures

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.4	0.29
PET	0	4.8	0.28	0.27
MaxS	1.45	32.73	17.87	14.56
DeltaS	0	25.58	9.36	23.45
DR	-8.19	3.37	-4.29	12.28
MaxD	-8.33	3.37	-5.08	12.54
MaxDeltaV	0	13.99	4.94	6.6

Tables 4.24 and 4.25 show results observed for 50% AVs and 50% HVs at the intersection of IH 35 and Wells Branch Parkway.

Table 4.24: Intersection of IH 35 and Wells Branch Parkway conflicts summary

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	13350	0	2	9477	3871
Run 1	1325	0	0	925	400
Run 2	1759	0	0	1275	484
Run 3	1139	0	0	816	323
Run 4	1169	0	0	803	366
Run 5	2108	0	0	1542	566
Run 6	1390	0	0	974	416
Run 7	1048	0	1	733	314
Run 8	1021	0	0	736	285
Run 9	1404	0	1	1010	393
Run 10	987	0	0	663	324

Table 4.25: Intersection of IH 35 and Wells Branch Parkway surrogate safety measures

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.24	0.22
PET	0	4.8	0.17	0.18
MaxS	0	32.34	18.31	11.3
DeltaS	0	29.66	11.85	27.45
DR	-8.23	3.32	-3.64	8.84
MaxD	-8.36	3.32	-5.23	8.63
MaxDelta V	0	15.51	6.25	7.69

4.6.6 Intersection of IH 35 and 4th Street

The simulation results for the network intersection of IH 35 and 4th Street indicated that the number of conflicts comprehensively decreased with the addition of AVs. Figure 4.14 summarizes the conflicts across various concentrations of AVs.

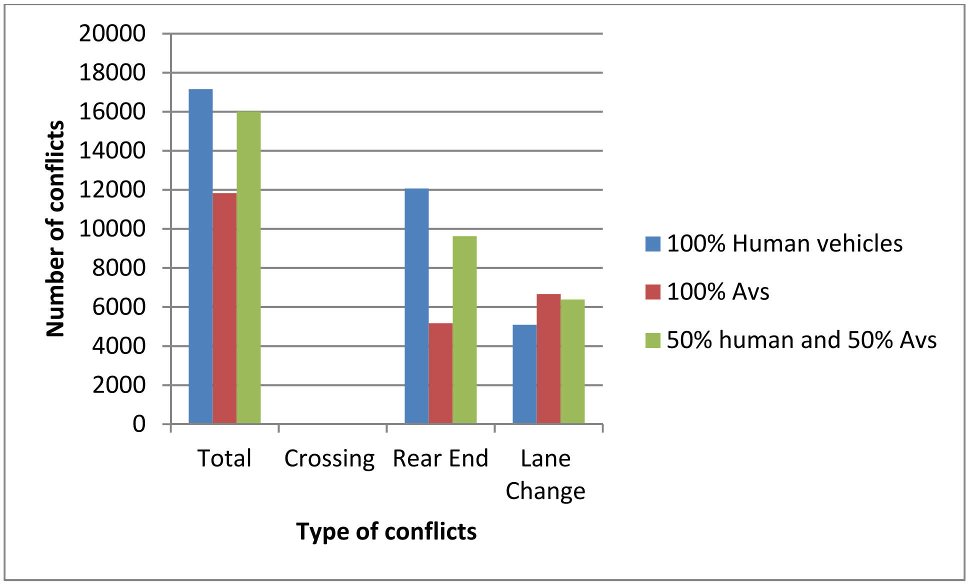


Figure 4.14: IH 35 and 4th Street conflicts disaggregated by type

At the specified flow, the MaxDeltaV and DeltaS values were found to decrease consistently with the increase in the concentration of AVs at the intersection of IH 35 and 4th street. MaxS, however, increased slightly for increasing AVs concentration. For example, the MaxS for all HVs is 15.3 m/s, while at 100% AVs it is 15.83 m/s, which is almost a 3% increase. The DeltaS for all HVs is 10.41 m/s, while at 100% AVs it is 8.20 m/s, which is almost a 22% decrease. Finally, the MaXDeltaV for all HVs is 5.49 m/s, while at 100% AVs it is 4.32 m/s, which is almost a 22% decrease (Table 4.26). Table 4.25 summarizes the total number of conflicts and other measures for the various scenarios predicted by SSAM.

Tables 4.26 and 4.27 show results observed for 100% AVs at the intersection of IH 35 and 4th Street.

Table 4.26: Intersection of IH 35 and 4th Street conflicts summary

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	11833	0	2	5171	6660
Run 1	1189	0	0	536	653
Run 2	1199	0	0	519	680
Run 3	1251	0	1	554	696
Run 4	1156	0	0	526	630
Run 5	1283	0	0	560	723
Run 6	1112	0	0	463	649
Run 7	1189	0	0	521	668
Run 8	1162	0	1	493	668
Run 9	1185	0	0	505	680
Run 10	1107	0	0	494	613

Table 4.27: Intersection of IH 35 and 4th Street surrogate safety measures

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.35	0.26
PET	0	4.6	0.29	0.37
MaxS	0	29	15.83	28.14
DeltaS	0	27.56	8.2	28.75
DR	-8.17	3.5	-4.6	12.39
MaxD	-8.35	3.5	-5.18	12.4
MaxDeltaV	0	14.66	4.32	8.02

Tables 4.28 and 4.29 show results observed for 100% HVs at the intersection of IH 35 and 4th Street.

Table 4.28: Intersection of IH 35 and 4th Street conflicts summary

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	17156	0	1	12067	5088
Run 1	1145	0	0	702	443
Run 2	1687	0	1	1136	550
Run 3	1550	0	0	1062	488
Run 4	2511	0	0	1932	579
Run 5	1251	0	0	787	464
Run 6	1805	0	0	1335	470
Run 7	1591	0	0	1113	478
Run 8	1910	0	0	1349	561
Run 9	1289	0	0	830	459
Run 10	2417	0	0	1821	596

Table 4.29: Intersection of IH 35 and 4th Street surrogate safety measures

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.22	0.2
PET	0	4.8	0.17	0.18
MaxS	0	31.72	15.3	22.58
DeltaS	0	28.57	10.41	27.85
DR	-8.37	3.1	-3.88	9.87
MaxD	-8.5	3.1	-5.19	10.07
MaxDeltaV	0	14.29	5.49	7.82

Tables 4.30 and 4.31 show results observed for 50% AV and 50% HVs at the intersection of IH 35 and 4th Street.

Table 4.30: Intersection of IH 35 and 4th Street conflict summary

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	16012	0	2	9629	6381
Run 1	1726	0	0	1027	699
Run 2	1485	0	1	873	611
Run 3	1767	0	0	1093	674
Run 4	1508	0	0	906	602
Run 5	1552	0	0	898	654
Run 6	1460	0	0	890	570
Run 7	1724	0	1	1072	651
Run 8	1668	0	0	991	677
Run 9	1683	0	0	1024	659
Run 10	1439	0	0	855	584

Table 4.31: Intersection of IH 35 and 4th Street surrogate safety measures

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.28	0.24
PET	0	4.8	0.22	0.29
MaxS	0	29.82	15.62	24.86
DeltaS	0	31	9.37	29.34
DR	-8.5	3.5	-3.88	10.29
MaxD	-8.5	3.5	-5.18	10.11
MaxDeltaV	0	15.99	4.94	8.18

4.6.7 Intersection of Manor Road and E M Franklin Avenue

The simulation results for the network intersection of Manor Road and E M Franklin Avenue indicated that the number of conflicts increased as the concentration of AVs increased from 0% to 50%, but then decreased as the concentration of AVs reached 100%. Figure 4.15 summarizes the number of conflicts across various concentrations of AVs.

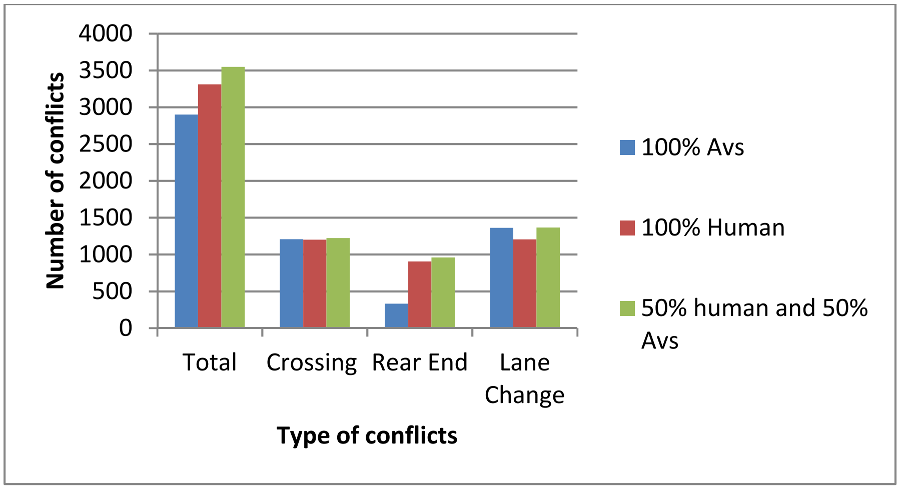


Figure 4.15: Conflicts at the intersection of Manor Road and E M Franklin Avenue

At the specified flow, the MaxDeltaV and MaxS values were found to decrease consistently with the increase in the concentration of AVs at the intersection of Manor Road and E M Franklin Avenue. DeltaS, however, increased slightly for increasing AVs concentration. For example, the MaxS for all HVs is 20.82 m/s, while at 100% AVs it is 20.43 m/s, which is almost a 2% decrease. The DeltaS for all HVs is 20.27 m/s, while at 100% AVs it is 20.57 m/s, which is almost a 1.5% increase. Finally, the MaxDeltaV for all HVs is 30.61 m/s, while at 100% AVs it is 10.84 m/s, which is almost a 65% decrease (Table 4.32). Tables 4.32 and 4.33 show results observed for 100% AVs at the intersection of Manor Road and E M Franklin Avenue.

Table 4.32: Intersection of Manor Road and E M Franklin Avenue conflicts summary

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	2901	0	1208	331	1362
Run 1	303	0	123	34	146
Run 2	275	0	111	34	130
Run 3	316	0	111	45	160
Run 4	286	0	115	32	139
Run 5	278	0	105	35	138
Run 6	317	0	138	39	140
Run 7	255	0	114	21	120
Run 8	291	0	135	28	128
Run 9	261	0	109	23	129
Run 10	319	0	147	40	132

Table 4.33: Intersection of Manor Road and E M Franklin Avenue surrogate safety measures

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.16	0.15
PET	0	3.2	0.09	0.07
MaxS	3.31	26.67	20.43	9.86
DeltaS	0.39	40.87	20.57	111.26
DR	-7.75	3.09	-1.55	12.23
MaxD	-8.1	3.09	-1.92	14.26
MaxDeltaV	0.21	22.21	10.84	30.99

Tables 4.34 and 4.35 show results observed for 100% HVs at the intersection of Manor Road and E M Franklin Avenue.

Table 4.34: Intersection of Manor Road and E M Franklin Avenue surrogate safety measures

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	3311	0	1201	905	1205
Run 1	365	0	128	97	140
Run 2	283	0	109	68	106
Run 3	446	0	144	147	155
Run 4	277	0	109	65	103
Run 5	353	0	119	114	120
Run 6	345	0	134	88	123
Run 7	276	0	109	55	112
Run 8	327	0	117	97	113
Run 9	327	0	116	102	109
Run 10	312	0	116	72	124

Table 4.35: Intersection of Manor Road and E M Franklin Avenue surrogate safety measures

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.14	0.14
PET	0	2.4	0.07	0.04
MaxS	2.27	27.71	20.82	6.31
DeltaS	1.08	43.19	20.27	110.09
DR	-7.66	2.59	-1.56	9.43
MaxD	-8.23	2.59	-2.19	12.45
MaxDeltaV	0.55	23.26	10.66	30.61

Table 4.36 and 4.37 show results observed for 50% HVs and 50% AVs at the intersection of Manor Road and E M Franklin Avenue.

Table 4.36: Intersection of Manor Road and E M Franklin Avenue surrogate safety measures

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	3549	0	1223	960	1366
Run 1	372	0	121	100	151
Run 2	296	0	104	76	116
Run 3	392	0	128	123	141
Run 4	335	0	127	75	133
Run 5	344	0	116	83	145
Run 6	384	0	138	94	152
Run 7	307	0	113	79	115
Run 8	378	0	133	112	133
Run 9	366	0	119	108	139
Run 10	375	0	124	110	141

Table 4.37: Intersection of Manor Road and E M Franklin Avenue surrogate safety measures

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.13	0.13
PET	0	2.6	0.07	0.04
MaxS	3	27.71	20.51	7.41
DeltaS	0.87	41.16	19.66	104.76
DR	-8.24	2.52	-1.68	10.1
MaxD	-8.36	2.52	-2.38	13.3
MaxDeltaV	0.44	22.14	10.35	29.04

In summary, the Vissim simulations and the subsequent SSAM analyses suggest that AVs may be safer on selected networks in comparison with HVs. It was observed that the number of crashes and their severity decreases as the concentration of AVs increases in the traffic. The results, however, were not completely consistent in trend. Certain measures, such as DeltaS and MaxDeltaV, showed unexpected patterns for some conditions. These discrepancies, however, were minor and no major anomalies were encountered. The reason for the observed discrepancies could be the difference in the behavior of AVs for different road networks; the AV and HV used for this analysis may also require better calibration to provide more realistic results.

4.7 Conclusions and Future Work

This chapter attempts to comprehensively anticipate the safety benefits of various CV and AV technologies, in combination, and in terms of economic costs and functional life-years saved in the U.S. The most recently available U.S. crash database (the 2013 NASS GES) was used, and results suggest that advanced CAV technologies may reduce current U.S. crash costs at least by $126 billion per year (not including pain and suffering damages, and other non-economic costs) and functional human-years lost by nearly 2 million (per year). These results rely on the three different effectiveness scenarios with market penetration rate of 100% of all CV- and AV-based safety applications. According to the 2013 GES crash database, of the eleven safety applications or combinations of safety applications, the one with the greatest potential to avoid or mitigate crashes is FCW associated with CACC. CICAS also offer substantial safety rewards, with total economic savings over $22 billion each year (and almost 1.24 million years saved). These two safety applications are estimated here to represent over 55% of the total economic costs saved by all eleven combinations of CV and AV technologies, suggesting important directions for government agencies and transportation system designers and planners. These two technologies may most merit priority deployment, incentives policies, and driver/traveler adoption.

There is little doubt that CAV technologies will offer some significant safety benefits to transportation system users. However, the actual effectiveness of these technologies will not be known until sufficient real-world data have been collected and analyzed. Here, their effectiveness assumes 90% market access and use (so technologies are available to all motorized vehicle occupants and are not disabled by those occupants), as well as different success rates under several assumption scenarios. Such assumptions come with great uncertainty, and the interaction between CAV systems and drivers/travelers. More on-road deployment and testing will be helpful, alongside simulated driving situations. It is also important to mention that connectivity is not needed in many cases, when AV cameras will suffice. But CICAS does require a roadside device able to communicate quickly with all vehicles. And NHTSA is likely to require DSRC on all new vehicles in model year 2020 and forward (Harding et al., 2014), so connectivity may come much more quickly than high levels of automation, in terms of fleet mix over time. Older vehicles may be made connected soon after, when costs are low (e.g., $100 for add-ons to existing vehicles) (Bansal and Kockelman, 2015) and the benefits of connectivity more evident to the nation. It is also useful to note that GES crash records have more attributes than those used here, including road types and weather conditions at time of crash. Future work may do well to focus on anticipating technology-specific safety benefits with more hierarchical pre-crash scenarios, combined with road types and weather conditions. Furthermore, the database used in this study only contains GES crash records, representing only U.S. driving context. For more detailed results, local crash databases, and databases in other countries, can be mined, which may suggest different benefit rankings and magnitudes.

The microsimulations of AVs indicated that the reductions in stochasticity in AV behavior resulted in significant improvements in safety in many intersection scenarios. However, because traffic models of AVs are recent developments in the literature, our car-following model may not be a completely accurate model of AV behavior when AVs become available to most travelers. AVs may further improve safety by sensing imminent collisions and making emergency braking or accelerations to avoid them. In addition, emergency braking of accelerations could reduce the severity of incidents by reducing the relative differences in velocity. On the other hand, safety behaviors for AVs require legal and philosophical analyses as well. AVs may enter situations in which any action or inaction will result in a collision, and the only choice available is to decide which collision will be the least damaging. Such questions cannot be answered by engineering alone, and therefore AV behaviors with respect to safety considerations are not fully known. Future work should refine the car-following model and address AV behavior in philosophically ambiguous situations.

Chapter 5 discusses the B-C analysis that the project conducted to identify the strategies that could be pursued by TxDOT. The B-C analysis was conducted using a time period of 40 years and a discount rate of 5%.

4.7.1 Vehicle Probe Data Collection

Vehicle probe data generated by systems and sensors onboard the vehicle (onboard equipment, or OBE) that can be aggregated at a higher level, allowing traffic management center (TMC) operators to gain better insight into high fidelity, real-time travel conditions and also historical trends. Examples of data include vehicle dynamics (speed, acceleration), emissions data (CO_2 generation, fuel efficiency), weather data (rainfall rate, temperature), roadway characteristics (surface roughness, debris identification), and many other data types. Data is collected onboard the vehicle at a periodic rate and cached until the vehicle is in range of an infrastructure device. Data is cached as a snapshot of information that includes the location of the vehicle, time the data was collected, and the sequence of data elements that were collected. Upon establishing a communications link with the infrastructure, typically an RSE, the OBE sends the data it has accumulated up to that point. The data is passed through the RSE to one or more software processes that can either use the data in real-time, such as displaying it on a map to a user with each data point shown where it was generated or measured (i.e., the location of the vehicle when the data is sent to the RSE is not relevant to the individual data elements), or store the data for later use. This data can be used in the same way as other data such as TSS to publish data to Event Management for the detection of events as needed.

Chapter 5. Benefit-Cost Analysis of CAVs

Many researchers, planners, and transportation operators predict that autonomous vehicles (AVs) will have a significant impact on the transportation system. To prepare for the changes accompanying new AV technologies, it is imperative that transportation agencies effectively prepare the infrastructure to ease the transition from a network dominated by conventional vehicles to one that could possibly see a significant share of AVs within the next several decades. The purpose of this study was to identify design and management strategies that could be employed by departments of transportation (DOTs) to transition to the future infrastructure. A benefit-cost (B-C) analysis was conducted to identify the strategies that could be pursued.

This chapter is divided into 10 sections. Section 5.1 provides a short overview, and outlines the operational strategies that were analyzed. Section 5.2 reviews the operational impacts of CAVs. Section 5.3 takes a broad review of the safety impacts of CAVs, and Section 5.4 outlines the potential of CAVs. Section 5.5 looks at the economic effects of CAVs, and Section 5.6 then reviews the deployment and maintenance challenges for infrastructure-based CVs. Section 5.7 reviews deployment strategies and challenges, Section 5.8 analyzes nine specific operational strategies, including demand management strategies and some initial conclusions. Section 5.9 outlines the B-C analysis methodology and results, while Section 5.10 discusses the results, and Section 5.11 presents conclusions and thoughts on future research directions.

5.1 Introduction

In the past few years, a significant amount of transportation planning research has focused on preparing for the onset of AVs. This research has coincided with advances in technologies related to AVs and CVs. Engineers, scientists and policy makers are currently developing the software, hardware, and regulatory environment needed to usher in AVs, which has left researchers with the question of how CAVs will affect infrastructure, how cities are planned, and how people travel. This section seeks to answer how the transportation infrastructure can be prepared in order to best take advantage of the new opportunities afforded by AV and CAV technologies.

The B-C analysis was conducted using a time period of 40 years and a discount rate of 5%. Since AV development is expected to occur over several decades, a longer project life was selected. The discount rate was selected by considering normal discount rates that transportation managers often use in B-C analysis. The following operations strategies were analyzed:

- CICAS
- RLVW
- SSGA
- SSVW
- Clearer pavement markings
- Road pricing
  - Variable tolling
  - Micro-tolling
- Smart intersections

Each of these strategies provides a different set of tools for the transportation managers, such as DOTs, to realize the safety and operational benefits of CAV use. For several of the strategies, quantitative benefit-cost ratios (BCRs) were estimated. With other strategies, engineering judgment was used to predict BCRs, due to the lack of simulation data needed to perform a more rigorous B-C analysis. Analytical results suggest that, among specific strategies envisioned here, the RLVW, SSGA, and SSVW safety strategies will provide the greatest social benefits, per dollar of DOT or roadway manager spending, since they are expected to reduce crash frequencies significantly. Clearer pavement markings may be a strategy to pursue for lower levels of CAV market penetration, because the sensors CAVs use for detecting objects and navigation need to detect visible markings; however, CAV technology is developing so that vehicles will not need to rely so much on lane markings for safe, steady movement.

Demand management strategies like variable tolling, micro-tolling, and managed lanes also appear to be sound investments to pursue, but more data is needed to provide quantitative BCRs for the tolling strategies. Based on traffic simulation data, smart intersections appear to have the potential to significantly reduce the amount of control delay experienced by users as AV adoption increases.

Though this B-C analysis is preliminary (and may be made more rigorous after more simulation data becomes available), it provides an important initial assessment of strategies that DOTs and other roadway managers should consider in the short, medium, and long term, as CAV technologies develop and public attitudes and opinions toward CAVs change.

5.2 Operational Impacts of CAVs

The introduction of CAV technology into the national transport system is expected to significantly affect how people travel and the amount of congestion that drivers experience. In Texas, drivers are estimated to experience over 560 million hours of delay per year (Fagnant et al., 2015). These hours contribute to losses in productivity, higher emissions, and increased fuel consumption. Using V2V technology, CAVs will be able to communicate with each other, which could be used to implement traffic operations strategies like flow smoothing, with the intention of reducing congestion. As market penetration of CAVs increases, road space can be used more efficiently by reducing headway between CAVs. More efficient use of roads will increase throughput significantly, thereby mitigating congestion's effects.

Fagnant et al. (2015) estimated the Level 4 CAVs' congestion cost savings for travel on Texas freeways at three different market CAV penetrations: 10%, 50%, and 90%, with cost savings shown in Table 5.1.

Table 5.1: Estimated congestion cost savings from CAV use

City	Impact	Market penetration			
		0%	10%	50%	90%
Austin	Annual Delay per Population (hr)	24.4	23.0	20.8	14.7
	Delay Reduction per Population (hr)		1.4	3.6	9.7
	Congestion Cost Savings per Population		$25	$64	$172
	Regional Congestion Cost Savings ($M)		$31	$79	$213
Dallas/Fort Worth	Annual Delay per Population (hr)	24.9	23.4	21.2	15.0
	Delay Reduction per Population (hr)		1.5	3.7	9.9
	Congestion Cost Savings per Population		$26	$65	$175
	Regional Congestion Cost Savings ($M)		$246	$621	$1,670
Houston	Annual Delay per Population (hr)	29.4	27.7	25.0	17.7
	Delay Reduction per Population (hr)		1.7	4.3	11.7
	Congestion Cost Savings per Population		$30	$77	$206
	Regional Congestion Cost Savings ($M)		$288	$727	$1,957
San Antonio	Annual Delay per Population (hr)	22.5	21.2	19.2	13.6
	Delay Reduction per Population (hr)		1.3	3.3	8.9
	Congestion Cost Savings per Population		$23	$59	$158
	Regional Congestion Cost Savings ($M)		$86	$216	$581
Others[38]	Annual Delay per Population (hr)	15.0	14.2	13.2	11.3
	Delay Reduction per Population (hr)		0.8	1.8	3.8
	Congestion Cost Savings per Population		$14	$32	$67
	Regional Congestion Cost Savings ($M)		$73	$162	$340
Statewide	Congestion Costs ($M)	$13,079	$12,319	$11,185	$8,078
	Congestion Cost Savings ($M)		$760	$1,894	$5,001
	System-wide Congestion Reduction (%)		5.8%	14.5%	38.2%

Source: Fagnant et al., 2015

These results suggest that CAVs could help significantly reduce delay on roads in Texas, if the state develops and deploys intelligent infrastructure that can take advantage of and harness new CAV capabilities. The results also show that delay should decrease as more CAVs are introduced. As a result, it is imperative that infrastructure is prepared to reap these potential benefits.

[38] El Paso, Laredo, McAllen, Brownsville, Corpus Christi, and Beaumont.

5.3 Safety Impacts of CAVs

Li and Kockelman (2016) estimated the economic costs and functional years lost in each of the 36 National Automotive Sampling System (NASS) General Estimates System (GES) pre-crash scenarios, and their results are shown in Table 5.2.

Table 5.2: U.S. economic costs of crashes resulting from NASS GES pre-crash scenarios

No.	Pre-Crash Scenario	2013 Economic Costs (Millions of Dollars)	Functional-years lost (Years)
1	Vehicle failure	$1,585	25,000
2	Control loss with prior vehicle action	$14,425	290,000
3	Control loss without prior vehicle action	$7,570	103,000
4	Running red light	$1,194	14,000
5	Running stop sign	$1,958	34,000
6	Road edge departure with prior vehicle maneuver	$13,419	264,000
7	Road edge departure without prior vehicle maneuver	$667	5,000
8	Road edge departure while backing up	$27	1,000
9	Animal crash with prior vehicle maneuver	$3,359	29,000
10	Animal crash without prior vehicle maneuver	$2,653	62,000
11	Pedestrian crash with prior vehicle maneuver	$5,086	125,000
12	Pedestrian crash without prior vehicle maneuver	$925	15,000
13	Pedalcyclist crash with prior vehicle maneuver	$1,221	24,000
14	Pedalcyclist crash without prior vehicle maneuver	$2,094	14,000
15	Backing up into another vehicle	$2,983	38,000
16	Vehicle(s) turning – same direction	$550	6,000
17	Vehicle(s) changing lanes – same direction	$6,948	60,000
18	Vehicle(s) drifting – same direction	$5,222	41,000
19	Vehicle(s) parking – same direction	$952	26,000
20	Vehicle(s) making a maneuver – opposite direction	$6,087	124,000
21	Vehicle(s) not making a maneuver – opposite direction	$24	1,000
22	Following vehicle making a maneuver	$2,496	29,000
23	Lead vehicle accelerating	$383	4,000
24	Lead vehicle moving at lower constant speed	$10,826	113,000
25	Lead vehicle decelerating	$15,545	140,000
26	Lead vehicle stopped	$27,304	293,000
27	LTAP/OD at signalized junctions	$884	6,000
28	Vehicle turning right at signalized junctions	$5,102	70,000
29	LTAP/OD at non-signalized junctions	$11,065	145,000
30	Straight crossing paths at non-signalized junctions	$9,151	103,000
31	Vehicle(s) turning at non-signalized junctions	$8	1,000
32	Evasive action with prior vehicle maneuver	$177	3,000
33	Evasive action without prior vehicle maneuver	$106	3,000
34	Non-collision incident	$174	2,000
35	Object crash with prior vehicle maneuver	$1,413	23,000
36	Object crash without prior vehicle maneuver	$5	1,000
37	Other	$5,423	81,000
	Totals	***$ 169,011***	***2,318,000***

Source: Li & Kockelman, 2016

A pre-crash scenario is an event that preceded a vehicular accident. Many of the strategies assessed in this project could potentially prevent one or more of the scenarios listed in Table 5.2, thus reducing crashes and creating significant cost savings. Li & Kockelman mapped CV, AV, and CAV safety applications to 36 pre-crash scenarios in Chapter 4 at Table 4.2. Their work shows that many of the new CAV technologies could have a significant impact on preventing crashes. Crash mitigation is a leading motivation for introducing CAVs to the market (Litman, 2015).

5.4 Assessing the Potential of CAVs

Adoption of CAVs are associated with both costs and benefits. Benefits expected from reduction in crashes and delay must be weighed against the costs of equipment, installation, and maintenance. These costs include those absorbed by the consumers using CAVs, and those borne by transportation agencies in preparing infrastructure for CAV compatibility. Fagnant et al. (2015) weighed their estimates of the potential congestion and safety benefits of introducing CAVs in Texas against the costs borne by the users of the CAVs. Their work produced BCRs, shown in Table 5.3, for the 10%, 50%, and 90% market penetration levels.

Table 5.3: Estimated BCRs for CAV adoption in Texas

		CAV Market Penetration		
		10%	**50%**	**90%**
Benefits	Congestion reduction ($/Veh/Year)	$318	$159	$233
	Economic crash savings ($/Veh/Year)	$454	$601	$689
	Comprehensive crash savings ($/Veh/Year)	$1,943	$2,565	$2,941
	Productivity and leisure ($/Veh/Year)	$1,357	$1,357	$1,357
	Sum of benefits ($/Veh/Year)	$3,618	$4,081	$4,530
Costs	Price of automation and connectivity capabilities ($/Veh)	$10,000	$5,000	$3,000
Net Present Values (using comprehensive crash cost savings) ($/Veh)		$13,960	$22,024	$27,000
Benefit-Cost Ratios (BCRs) (using comprehensive crash cost savings)		2.4	5.4	10.0

Source: Fagnant et al., 2015

Fagnant et al.'s (2015) results suggest that CAV adoption should be an excellent investment for transportation system users, as adoption rates rise. Their work considered costs to travelers, while this chapter focuses on the DOT perspective.

5.5 Economic Effects of Automated Technologies

AVs have the potential to generate widespread improvements in safety, time savings, and fuel savings, but the value of AVs stretches far beyond this scope into the broader economy. Although AVs will naturally cause losses in some industries, the overall impact on the U.S. economy should be positive, as Morgan Stanley estimates an overall potential value of $1.3 trillion, or 8% of the entire U.S. GDP (Lewis 2014). An understanding of the trajectories of the specific business sectors affected, both positively and negatively, by AVs is essential in effectively preparing for the economic impact.

Previous papers by companies like KPMG, Morgan Stanley, and McKinsey and Co. as well as research from Dr. Fagnant and Dr. Kockelman have thoroughly investigated different aspects of the effects of AVs on the U.S. transportation system and economy. This section will focus on the economic effects of fully AVs on specific markets by compiling and integrating economic research from the foremost articles and studies on the topic. The markets evaluated are ordered beginning with the most directly and thoroughly impacted industries and ending with the more tangentially related markets. Finally, this section ends with a look at the more wide-ranging effects on the economy such as improvements in safety, productivity, and fuel efficiency. With the examination of all these industries along with the more pervasive effects, we will get a better idea of the big picture impact on the U.S. economy.

5.5.1 Industry Impacts

Automotive

The industry most obviously and directly affected by the emergence of AVs is the automotive industry. The auto industry is one of the driving forces of the U.S. economy, employing 1.7 million people, providing $500 billion in compensation annually, and accounting for about 3% of GDP. Driverless automobiles will not only influence the use and design of automobiles but also will redefine the business positioning of companies currently inside and outside the automotive industry. In a fully developed industry that has started to fall victim to stagnation and a decreasing interest from the youth population, AVs have the potential to revitalize automotive companies everywhere (The Economist 2012).

One possible expansion in the market for vehicles will come from the increase in Vehicle Miles Traveled (VMT) due to the ability of children, disabled, and elderly to enjoy the convenience of automotive travel without the liability of physically driving the vehicle once systems become reliable enough to allow the legalization of completely autonomous operations (The Economist 2012). An additional consideration for the effect to VMT, however, is that automobile ownership may "dematerialize" as the technology develops even further, as a sort of "on-demand" car rental service is likely to develop (Diamandis 2014). Only 12% of all vehicles are on the road at the peak in rush hour, making vehicle sharing a very viable option (Silberg, Manassa, Everhart, Subramanian, Corley, Fraser, Sinha 2013). If vehicle sharing overtakes a significant part of the automotive market, it could result in a decrease in personal demand by millions of units (Silberg, Wallace, Matuszak, Plessers, Brower, Subramanian 2012). Forbes Magazine (Diamandis 2014) estimates that, all in all, this fact could cause the cost of transportation per mile to drop five- to ten-fold. If SAVs gain a large share of the market but people continue to ride independently in these autonomous taxis, VMT may increase due to unoccupied travel time between travelers.

Alternatively, if carpooling and hub-and-spoke models for vehicle sharing become more widespread, VMT will decrease. According to a report by the University of Michigan Transportation Research Institute, AVs could cause many families to choose to own just one car rather than two, if there is limited "trip overlap" for different members of the family (Schoettle, Sivak 2015). In the most extreme case, AVs could cause a drop from 2.1 cars per household to 1.2 cars per house hold, on average, representing a 43% reduction in the average number of vehicles per household (Schoettle et al. 2015). The real number will likely not be quite so significant, as people value the convenience of having flexibility to use a car at all times, but some decrease should be evident. A decrease in vehicles owned per household would directly decrease the number of vehicles purchased from automotive manufacturers. Additionally, VMT will not decrease unless people begin to accept carpooling or hub-and-spoke mobility systems, which involve multiple people traveling the same route. It is unclear how significant the factors affecting demand in each direction will be, but automobile companies will undoubtedly face a significantly different industrial landscape.

Along with the demand shifts in the market for the automobiles, companies will be required to strategically position themselves in order to adapt to the turbulent evolution of the fundamental characteristics of the industry. Once fully autonomous cars become pervasive, greater emphasis will be placed on software and digital media in comparison with the basic vehicle performance, forcing organizations to specialize in certain areas. A Morgan Stanley report (Jonas, Byrd, Shankar, Ono 2014) on the outlook on technological advances in the automotive business (namely alternative energy and autonomy) suggests that the auto industry could be completely reorganized into three main categories of providers: hardware manufacturers, software suppliers, and integrated "experience" creators.

Hardware involves the car essentially as we know it today (90% of the value of a current car), and companies that choose to specialize in this segment will continue to design and manufacture the body, powertrain, interior, lighting, and other basic components. This position is likely for smaller car companies without a competitive advantage in software development, because they will not be able to invest enough resources to generate comparable intelligent in-car systems. These companies will outsource the software to businesses that specialize in automotive operating systems. Due to the increased importance of software, hardware will become increasingly commoditized and only the most critical hardware components will command significant pricing power, possibly dropping the relative value of hardware to 40% of the value of the car (Jonas et al. 2014). In order to deal with decreasing margins on hardware sales, strong car companies will need to add value through carsharing, multi-modal journey planning, and other mobility-promoting services, according to Martyn Briggs, the Mobility Programme Manager at Frost & Sullivan (Feick 2013).

Software in a car currently makes up approximately 10% of its value, and, although it influences many functions in the automobile today, these interfaces are largely independent of each other. In autonomous cars, these software components will need to become coordinated into a central, universal operating system, controlling the powertrain, infotainment, and autonomous functionality, potentially representing 40% of the car value (Jonas et al. 2014). Large existing auto manufacturers, auto suppliers, and technology companies such as Google, Apple, and Microsoft are likely to produce this function of the car. Similar to the smartphone industry, the software-focused companies will sell and install their operating systems in cars of companies specializing in hardware, while car companies with large sums of resources will be able to invest in their own software development to generate a cohesive, integrated experience. Although this evolution may decrease margins in the hardware segment, the increasing value of software gives strong, wealthy automakers a new opportunity to generate revenue from another source and opens up the market for tech companies that never before would have had a hand in the auto business.

Electronics and Software Technology

With the potential opening in the automotive market in the software and in-car entertainment systems, technology firms might have the most to gain from autonomous cars. Technology firms could be brought into the mix simply as providers of entertainment or as large players in the car production process due to their competitive advantage in artificial intelligence.

A powerful effect of autonomous cars on the technology sector will likely be in the development of artificial intelligence and other technology for enabling a driverless experience and the integration of software in the car into a cohesive central operating system. Large technology firms have the opportunity to exploit their vast knowledge and resources to become providers of at least automotive computing power and potentially even enter the car market with vehicles of their own. Google has already developed autonomous car systems that have travelled over one million miles in California, with only 12 accidents, none deemed the responsibility of the self-driving vehicles (Google 2015). Much speculation has surrounded Apple entering the autonomous car game with the supposed name "Project Titan" for its automotive venture (Price 2015). Mark Lyndon, director at Intel Capital, confirmed that Intel recently launched a $100 million Connected Car Fund to "spur greater innovation, integration, and collaboration across the automotive technology ecosystem." (Silberg et al. 2012, p. 24)

With all these big players investing significant time and capital into autonomous cars, it is almost certain that they will play a large role in this revolution and they stand to gain large profits from it. Morgan Stanley estimates the percent value of the car that software represents could jump from 10% to 40% in an autonomous car environment (Jonas et al. 2014). The gains from margins on software sales, along with the potential to integrate software into an entirely proprietary automobile, present potential for huge profits for technology firms. One challenge technology companies could face is the cyclical, price-sensitive nature of the automotive industry that is not as profound in the electronics and software market (Jonas et al. 2014). However, due to the companies' continued basis in the software component of the automobile, these effects will not be as significant. Overall, the profits from the second most expensive item most people purchase after their house should prove too tempting to ignore. Technology firms might stand to benefit the most from the autonomous car revolution.

Trucking Industry and Freight Movement

The economics of the trucking and shipping industry could also experience a significant boost from the development of AVs. Trucking companies could create convoy systems, allowing long distance drives with large quantities of goods and eliminating the need for a limit on the hours of service of truck drivers and freeing up productive time during the drive. With intermodal transportation and logistics systems, the trucks could travel along major highways, transfer cargo at regional distribution centers, and then branch off for the final transfers directly to the packages' destinations. This new system would improve safety and efficiency, saving trucking companies immense amounts of fuel, time, and money.

The development of autonomous technology in commercial vehicles will likely lead the way in AV implementation, as some of the largest economic incentives are available in freight transportation. The process has begun already with vehicles that move within contained environments- warehousing and autonomous loading and transport. Vehicles that transport goods within a warehouse include the KNAPP Open Shuttle, SwissLog RoboCourier, and Jungheinrich Auto Pallet Mover (Heutger, Kückelhaus, Zeiler, Niezgoda, Chung 2014). These small cargo vehicles improve efficiency within warehouse procedures, eliminate the need for humans in operating machinery such as forklifts, and limit the necessary space for parking within the warehouse. Autonomous technology has begun to be expanded into larger yards, harbors, and airports and will continue to expand in these environments. The contained environment of a yard limits the amount of variable traffic, and the given entities have control over all vehicles within the area. In Harbor Container Terminal Altenwelder in Germany, container handling is almost totally automated, utilizing 84 driverless vehicles and 19,000 transponders installed in the ground, significantly increasing the speed and efficiency of the cargo operation (Heutger et al. 2014).

The next step of autonomy in commercial vehicles is assisted highway trucking, in which Level 1 or Level 2 AVs will help reduce truck collisions, with features such as lane centering and adaptive cruise control. After assistive systems, full AVs will allow convoying, in which the lead driver of a chain of multiple trucks is in control of driving, but the following trucks require no human input, but are connected wirelessly to the lead truck. Convoys do create issues with other traffic merging and/or changing lanes, but this system could reduce accident rates and could cut fuel consumption by 15% (Heutger et al. 2014). Even if drivers were still required in the following vehicles, the time convoying could be counted as rest time, since the occupant/truck attendant could perform other activities, further extending the efficiency of the freight transportation system.

Many examples of autonomous trucking in closed environments already exist, and companies are investing in advancing this application of autonomous technology. The New Energy and Industrial Technology Development Organization, a research organization in Japan, has successfully tested a system in which one driver leads three other trucks in a convoy at 50 miles per hour with a spacing of four meters using roof-mounted LIDAR systems (McKinsey 2013). Once autonomous cars become viable, this system can possibly be adapted to be operated without a leading driver, although this full development will have a much longer time span. The report by McKinsey also states that the Australian mining company, Rio Tinto, has used around 150 partially autonomous trucks in their operations, routing and unloading material without an operator. Additionally, Daimler, the parent company of Mercedes-Benz, has already created a prototype for a long-haul autonomous truck (USA Today 2015). McKinsey estimates that the economic gains of driverless cars in the trucking industry could be range from $100-500 billion per year by 2025 (McKinsey 2013).

Although the automation of truck driving would save the companies themselves large sums of money, these savings would largely come from the elimination of the wages of the truck drivers. According to the American Trucking Association (2015), the industry employs over 3 million truck drivers and the automation of driving poses a huge threat to the livelihood of these truck drivers. At this time, however, there is already a shortage of about 25,000 truck drivers because of the long hours and time away from home (American Trucking Association 2015). So, AVs could simply increase the capacity of logistics companies, allowing for more shipments. AVs would undoubtedly be of massive benefit to the freight transportation and trucking industry but pose some risks for the employment of millions of truck drivers.

Personal Transport

Autonomous cars could also transform the transportation industry beyond the automotive industry, affecting trains, planes, and public transport. When vehicles no longer require an operator, occupants will be at liberty to use that time for productive work or even sleep. This "found time" on car trips might decrease the demand for alternative forms of transportation (Diamandis 2014). For example, if a destination is 10 hours away by car, a family or businessman may opt to make the trip overnight, sleeping while the car takes them to the destination, instead of making an airline flight. Bus, airline, train, and car rental companies could all be affected by the AVs' added convenience. A possible development for bus companies to adapt to driverless vehicles is to develop a connected convoy system to transport a greater number of passengers on long trips.

The biggest change in personal transportation will more likely come in short commutes. With autonomous car technology, companies could develop an "on-demand" taxi service known as SAVs Shared Autonomous Vehicles that would make human-driven taxis obsolete. In fact, General Motors already has an autonomous taxi prototype that is summoned by a phone app. According to Frost & Sullivan (2013), Google is leading the way in a carsharing business model and could be leading toward decreased car ownership. At peak vehicle usage in rush hour (around 5 PM), less than 12% of all personal vehicles are on the road (Silberg et al. 2013). The Brookings Institute makes an even bolder claim that vehicles sit unused an average of 95% of the time

(Brookings 2015). Vehicle sharing has the potential to decrease these inefficiencies in our current transportation models. At the very least, autonomous cars will take a bite out of the alternative personal transportation providers like taxis, buses, and trains, and they could extend as far as redefining our car usage, making vehicle ownership more of a luxury than a necessity.

Auto Repair

With 360-degree sensors, no distractions, no drunk driving, among other characteristics, driverless cars will be able to largely eliminate car crashes caused by human error, which amount to over 90% of crashes in the U.S. currently (McKinsey 2013). Collision repair shops will lose a huge portion of their business. Indirectly, the decreased need for new parts for crashed vehicles would also decrease the demand for manufactured parts from steel producers and part manufacturers. Different levels of market penetration will cause proportionally different percent reductions in crashes. In 2013, almost $30 billion in repairs were caused by vehicle crashes in the United States (Stahl 2014). Assuming 25% reduction in crashes, the industry would lose $7.5 billion, and at a 50% reduction, auto repair dollars would decrease by $15 billion. Finally, at 100% market penetration in the best case scenario, we would experience a 90% reduction in crashes and a $27 billion loss to the industry.

Some auto shops could find new opportunities in aftermarket personalization of vehicles, customizing the new, more important interior of the autonomous car, but this will likely not be enough to cover the losses from their usual business (McKinsey 2013). As the level of autonomy increases and crashes fall, a large percentage of collision repair shops will lose profitability and will be forced out of business. Despite the societal gain due to decreased crashes, collision repair shops will face a large detriment from driverless cars.

One effect that could be of benefit to the auto repair industry is the increased road time of autonomous cars through sharing systems. Although there may be fewer total cars, the cars in use could be on the road for 12 hours per day, which will cause an increase in the miles travelled and the overall need for maintenance. Autonomous cars will still provide an increase in safety, but this increased number of road hours allows for more opportunities for crashes that would give business to the collision repair shops. The exact effect on the industry in either direction is unclear, but the net tilt is likely be to the detriment of collision repair businesses.

Medical

Another industry that will lose business from the improved safety of AVs is the medical industry. Approximately 2 million hospital visits (The Economist 2012) and 240,000 extended hospitalizations per year in America are due to traffic accidents Driverless cars would eliminate a large majority of these medical visits. McKinsey & Co. (2013) estimated that the combination of reduced repair and health care bills could save consumers $180 billion, which would generate proportional losses for service providers. NHTSA estimates that motor vehicle crashes accounted for $23 billion in medical expenses (NHTSA 2015). With a 25% crash reduction, this accounts for a loss of $5.75 billion in the medical industry, $11.5 billion at a 50% reduction, and $20.7 billion at a 90% reduction. Although there will also be savings from the decreased need for supplies and doctors, and space could be cleared in overcrowded, long-wait emergency rooms, the financial situation will be significantly altered for medical providers. Also, a large proportion of organ donations come from automobile crash victims who are registered organ donors, since they are younger and healthier at the end of their lives. Hospitals and emergency rooms profit significantly from car accidents and could lose a large percentage of their business.

Insurance

Safety improvements will require insurance agencies to adapt and possibly reconstruct their fundamental business models. Currently, insurance companies sell policies to individual vehicle owners and human drivers are liable for car crashes. Insurance agencies currently net $180 billion annually in the USA insuring against automobile accidents and the related medical costs (Desouza, Swindell, Smith, Sutherland, Fedorschak, Coronel 2015). When driving becomes the job of computers, however, the issue of whether the driver is liable for the crash becomes much more ambiguous. Automakers and the vehicle's software providers will likely become the main responsible party and will need to purchase insurance for technical failure of the automobiles, making personal policies more limited in scope (Silberg et al. 2012). Liability may be placed on the driver for authorizing driving in wet, icy, or otherwise unsafe conditions, causing a need for some coverage. However, greater responsibility, under normal circumstances, will likely shift to the software and hardware manufacturers.

Additionally, the added safety of CAVs that are nearly error-free will reduce the number of crashes significantly. According to a report by KPMG (Albright, Bell, Schneider, Nyce 2015), over 90% of accidents each year are caused by driver error and accident frequency could drop as much as 80% with commercially viable Level 4 fully AVs (Albright et al. 2015). Even the automation of parts of the driving task has decreased insurance claim frequency. David Zuby, executive vice president and chief research officer of the Insurance Institute for Highway Safety, claims that "vehicles equipped with front crash prevention technology have a 7–15% lower claim frequency under property damage liability coverage than comparable vehicles without it" (Albright et al. 2015). KPMG (Albright et al. 2015) also hypothesizes that costlier technology under the hood of autonomous cars could increase the average accident expense from today's $14,000 to around $35,000 by 2040.

Ultimately, KPMG estimates that AVs could shrink the auto insurance industry by as much as 60% (Albright et al. 2015). With the current revenue of the auto insurance industry at approximately $220 billion, this decrease could represent a loss of $132 billion. Insurers will need to develop fewer but larger corporate policies to maintain their businesses. Vehicle owners will still need theft and comprehensive coverage for hail, flooding, and other natural damages and a more limited liability coverage and this will likely cause a decrease in premium per policy (Insurance Business 2015). Overall, this could make small auto insurance companies based in personal policies less viable and give more power to large businesses based in corporate contracts. Since there are far more insurance companies than auto manufacturers, this push for large policies for autonomous systems will cause competitive insurance pricing and big winners and losers in the battle for these corporate contracts.

Legal Profession

The result of fewer accidents from the automation of driving will likely challenge the profession of many attorneys. According to Judge David Langham (2015), around 76,000 attorneys in the United States specialize in personal injury. Law school is already becoming a less desirable path because of a current oversupply of attorneys, and the decrease in demand for personal injury lawyers would hurt career prospects even further. With an average liability claim for bodily injury of $15,443, a total number of crashes of around 5.5 million in 2012, and an average contingency fee of around 33 to 40%, the economic implications of this development are immense adding up to potential losses as much as $3.2 billion for personal claim lawsuits (Langham 2015). Although lawyers will always be necessary for many different cases, AVs could put a dent in the profession. The detriment to the profession could be offset by population growth and an increase in tort claims. Regardless, the landscape of the legal profession will be much different, at least in the scope of personal claims.

Construction and Infrastructure

Another AV impact is an altered need for infrastructure and construction of parking lots and new roadways. A potential increase in traffic efficiency would decrease congestion and the need for new, bigger roadways. If vehicle sharing reaches a sufficient level of development, a decreased need for parking would result and, thereby, reduce the demand for new parking lots and garages. Despite these increases in efficiency, these decreases in demand will likely be somewhat offset by the increase in VMT due to greater access and population growth. The designers and contractors of these large structures will get less of the business they are used to and need to adapt their businesses to include other types of infrastructure as DOTs reallocate their money to different projects.

Additionally, the way in which roadways are maintained and the number of component structures required may change. When vehicles become fully autonomous, we may no longer need extra-wide lanes, guardrails, traffic control signals, wide shoulders, rumble strips and other measures because of increased safety, and makers of these components will lose a source of income. Data can be used by DOTs to analyze road use patterns and better plan the maintenance and improvements that are still needed. KPMG (Silberg et al. 2012) estimates that intelligently controlled intersections could perform 200–300 times better than current traffic signals. KPMG also states that platooning could increase the effective capacity of roadways by as much as 500%, and with the combination of all factors the make a "conservative" estimate of a 10% reduction in infrastructure investment, saving around $7.5 billion per year (Silberg et al. 2012).

The infrastructure that is needed could be revolutionized alongside automobiles. An important component of creating connected autonomous cars is vehicle-to-infrastructure (V2I) communication. GPS, sensors, and 3-D planning, design, and construction tools can be used to help plan, design, and build more integrated and efficient transportation systems. With wireless transponders called Roadside Units or other smart embedded sensors, cars and roads can exchange information about curvy roads and low bridges, risks such as construction, and information about traffic density, flow, volume, and speed (Bennett 2013). In order to remain competitive, contractors that base their business on large government commissions for highway and infrastructure construction will need to be on the cutting edge of this technology.

Land Development

AVs will change the way transportation for people in all parts of the nation, and, therefore, will impact our habits and land use. AVs will likely transform the national parking system. According to Eran Ben-Joseph, parking lots and garages cover more than one-third of the land area in some U.S. cities (Diamandis 2014), creating unsustainable urban dead zones in centers where population density is increasing rapidly. Driverless cars will help mitigate this issue of overcrowding by allowing people to be dropped off at their location without the need to find a nearby parking spot. On top of this, vehicle sharing may keep vehicles in more constant use and serve more people, further decreasing demand for parking infrastructure. According to a study by McKinsey & Co., the property savings from freed up land from parking could add up to $190 billion in the U.S. alone (Woodyard 2015). The land area previously used for parking could be converted into housing, parks, or other useful developments that replace these parking dead zones.

Another possible impact of AVs on land development is the extension or contraction of urban sprawl. The automobile is the original invention that caused the development of suburban neighborhoods due to the increased distance one could travel in a given period of time and the fact that land further from city center costs less. AVs could allow for a decrease in time of commutes and an increase in productivity during the commute as the passenger is no longer required to focus all attention on driving, which could increase the draw of suburban housing. With the ability to engage in activities other than driving during the commute, the cost of transportation declines, increasing the value of living further from the urban core (Anderson, Kalra, Stanley, Sorensen, Samaras, Oluwatola 2014). Alternatively, AVs could cause a loosening in the urban real estate market, reducing the cost of urban living and encouraging families to move into town (Greeting 2014). Even with a freeing of urban space and potentially decreasing land prices, there is a limit to the total area of land in a city center and population continues to expand, which should cause the scenario of city expansion to dominate as opposed to a contraction.

Digital Media

The extension of digital media into the autonomous car environment will open up the market for even more users and, thereby, more sales. At the point of complete autonomy, commuters that usually spend time vigilantly watching the road (or dangerously multitasking on their smartphones) will demand greater integration of digital media features into their automobiles. Content providers like YouTube, Netflix, and social media networks will see a large benefit from the increased time and desire for their services on commutes.

Additionally, a study by McKinsey & Co. (2013) suggests that internet shopping could receive a large bump from this added free time, stating that each additional minute occupants spend on the internet could generate $5.6 billion annually, a total of $140 billion if half of the time of the average round-trip commute (25 minutes) is spent surfing or shopping. A possible loss due to this greater entertainment flexibility for drivers is a decreased demand for radio and recorded music. No longer will drivers be captive to audio-only entertainment, allowing them to forgo their usual radio programs for more stimulating visual ones. The boon for the overall entertainment market, however, could be quite significant, as a report from Morgan Stanley (Jonas et al. 2014) suggests the percent value of content in the automotive industry could shift from minimal to almost 20% of the value of the car (over $6,000 for the average cost of a car).

Law Enforcement

With human error and misbehavior in driving significantly reduced, traffic cops and parking wardens will no longer be as important. Drunk driving, speeding, parking and other traffic violations will become a thing of the past and the size of the police force will decrease (The Economist 2012). A survey by the Bureau of Justice Statistics shows that 31 million people were involuntarily stopped in 2011 and more than 85% of those stops were traffic related, and over half of all contact between civilians and police is related to vehicles (Zagorsky 2015). Another side effect of increased traffic obedience will be a loss of revenue for governments, as traffic fines make up a significant source of money.

According to the National Motorists Association (Bax 2008), the traffic ticket industry brings in between $7.5 to $15 billion. According to The Arizona Republic, however, ticket-related revenue was approximately $10.8 million, or 1.1%, of Phoenix's $1.03 billion budget in 2014 (Giblin 2015). Although $10 million is significant, a simple 1% of the city's budget is recoverable from other sources. Small towns, however, may be more strongly affected by law-abiding autonomous cars. While only five towns in Colorado earned more than 30% of revenue from traffic fines, the small city of Campo generated 93% of its budget from fines and forfeitures in 2013 (Rocky Mountain PBS 2015). These results are outliers of "speed trap" towns, but still this shift would be significant to these municipalities.

Government officials in small cities will have to find a way to adapt to this loss. A decreased payroll due to the decrease in highway patrol officers will offset some of the revenues loss, but governments could also replace some lost revenue by charging infrastructure usage fees (Silberg et al. 2012). One way to enable this solution with an established system is create more toll roads or even separate toll roads, similar to high-occupancy-vehicle (HOV) lanes, for autonomous cars that will be of value due to decreased traffic. Traffic tickets will not be eliminated until there is 100% market penetration of AVs, but the decreases will begin to be felt gradually and local and state agencies will want to prepare for this change.

Oil and Gas

A more efficient system of driving will also cause ripple effects in the oil and gas industry. More efficient, computer-controlled driving, lighter, more fuel-efficient vehicles, platooning, and efficient infrastructure will contribute to an overall improvement in fuel efficiency (Silberg 2012). The Texas Transportation Institute estimated that congestion costs Americans 4.8 billion hours of time, 1.9 billion gallons of fuel, totaling $101 billion in combined delay and fuel costs (Silberg 2012). Platooning could reduce highway fuel use by up to 20% just due to the decreased drag coefficient from drafting (Silberg 2013). The decreased need for parking will improve fuel efficiency as well, as one MIT study found that 40% of total gasoline use in cars in urban areas is spent looking for parking (Diamandis 2014). All of these factors suggest that drivers would demand less gas for their cars. However, the improvement in fuel efficiency could also be joined by an increase in vehicle miles traveled (VMT) due to the newfound convenience and expanding housing limits. It is not certain which way oil consumption will shift with autonomous cars, but it will definitely change the landscape of the oil and gas industry.

5.5.2 Economy-Wide Effects

AVs will increase the capacity of the nation's transportation system due to improvements in efficiency. First, with well-developed, accurate computing systems, traffic crashes, which account for 25% of traffic congestion, will be greatly reduced because approximately 93% are due to human error (Fagnant & Kockelman 2013). This fact will not only increase roadway capacity but also save potentially around $563 billion from the reduction in injuries and deaths of one of the largest killers in America (Jonas et al. 2014). Additionally, congestion will be reduced by the increased efficiency of coordinated vehicle speeds and traffic flow, due to data sharing between cars and synchronization of traffic signals, enabling a further increase in effective roadway capacity. The Center for Urban Transportation Research (Pinjari, Augustin, Menon 2013) estimates that the connection of AVs will cause a 22% increase in highway capacity at 50% market penetration, 50% capacity increase at 80% market penetration, and 80% increase at 100% market capacity. The increase in roadway capacity will likely be limited by a number of factors as there is a finite limit to roadway capacity even in ideal conditions. VMT could be increased, thereby increasing demand and decreasing the effective roadway capacity, both due to population growth and increase in accessibility. Population growth increases the raw number of potential drivers/riders. If AVs allow elderly and children to travel independently, an additional increase in VMT would occur due to increased access to previously unserved individuals. Although the magnitude of this change is widely debated and the gains will not be reflected until the AV fleet has significant market penetration, the benefits will be significant and will have improved energy efficiency and save the state and federal DOTs large sums of money.

Once the cars reach Phase 4 of autonomy with widespread adoption, they will enable children, elderly, and disabled people access to transportation. This will increase VMT and, thereby, slightly limit the decrease in congestion, but the increased efficiency should outweigh these effects (Pinjari et al. 2013). More importantly, this will allow a greater percentage of the population greater mobility that can also improve productivity nationwide. Additionally, productivity will be increased by the added time that can be used for other tasks, like working on the trip to the office. According to Forbes Magazine (Diamandis 2014), AVs could save over 2.7 billion unproductive hours in work commutes, generating an annual savings of $447.1 billion per year in the U.S. alone (assuming 90% AV penetration). Also, fuel savings could amount to $158 billion, due to a 20-30% increase in fuel economy due to smooth driving and cruise control (Jonas et al. 2014). This estimate, combined with $488 billion from crash costs, $507 billion from productivity gain, $11 billion from fuel loss from congestion, and $138 billion from productivity savings, amount to total savings just from the improvement of basic safety and efficiency factors from autonomous cars accounts for $1.3 trillion in the U.S., or 8% of the U.S. GDP, and as much as $5.6 trillion worldwide (Jonas et al. 2014).

Some effects brought on by AVs could act counter to and limit these gains. Once AV sharing is put into action, although fewer cars will be needed, those in use will accrue more miles and require maintenance more often. Additionally, the increased convenience and affordability may encourage more vehicle travel, offsetting the pollution and crash benefits (Litman 2015). Despite uncertainty in the precise numerical effects of autonomous cars and the requirement of significant market penetration, the logic behind and the likelihood of their development is undeniable and will be felt in our economy throughout various industries. The economic effects of AVs will extend beyond the simple crash, productivity, and fuel saving into every facet of the American economy.

5.5.3 Conclusions

AVs will transform our economy and change the landscape of almost every industry. Although some sectors will be more significantly affected than others, ripple effects will be felt throughout most, if not all. Change will not come overnight. The technology still has a long road of development ahead and market penetration will define the size of the impact of driverless vehicles. With the assumption that autonomous cars will eventually become pervasive, or at least hold a large share of the automotive market, it is assured that they will have a strong economic impact, potentially as much as $1.3 trillion or more. In order to prepare for this revolution, we must be aware of the potential effects so that we can alter our established systems to accommodate these changes. Change is coming, and we must be prepared to adapt.

5.6 Deployment and Maintenance Challenges for Infrastructure-Based CV Technology

5.6.1 Introduction

CV hardware and software are in the early stages of development, and are expected to enter the U.S. marketplace within 1 to 2 years. Because this technology will be integrated into vehicles that operate on U.S. roads, their regulation, in part, falls under the authority of the NHTSA. The

USDOT CV program is also heavily focused on using the DSRC technology that operates in a licensed band of the RF spectrum, which is regulated by the Federal Communications Commission. A number of "applications" have already been identified, and their essential functions and message protocols defined; however, as the technology progresses and is adopted by consumers, additional applications will emerge.

Vehicle-to-X (V2X) technology refers to any technology that is sending or receiving messages with a CV-equipped vehicle. This may include other vehicles, infrastructure devices, pedestrians, etc. The primary technology identified for V2X applications is DSRC; however, other technologies remain viable alternatives to DSRC in specific circumstances, primarily for non-safety-critical applications. Table 5.4 lists the potential CV communication technologies, their current maturity level, and their likely near-term evolution.

Table 5.4: Potential CV communication technologies

V2X Technology	Current Maturity	Likely Evolution
DSRC (Dedicated Short-Range Communi-cations)	5.9 GHz DSRC has been extensively tested in the USDOT's vehicle infrastructure integration (VII) Proof of Concept, Safety Pilot, and other related research projects. However, standards governing this technology remain somewhat in flux. Applicable standards are IEEE 802.11p, IEEE 1609, SAE J2735, and SAE. The low-latency and protected (licensed) spectrum of this technology makes it ideal for safety-critical applications.	The DSRC standards are expected to stabilize over the coming years, and DSRC hardware is expected to have progressed through certification programs. Based on the NHTSA direction, the V2V portions of SAE J2735 and SAE J2945 will be more mature than their V2I counterparts, but the lower-level IEEE standards should be stable. The potential sharing of the DSRC spectrum with unlicensed devices could have an impact on the reliability of CV applications.
Cellular	Cellular technology is mature and the current providers are experienced in the introduction of new generations of technology (e.g., 3G, 4G, 5G, and LTE).	Coming advances in cellular technology will allow it to be used in some of the safety-related applications. The primary challenge with using cellular for CV communications is the network access and data ownership models of private telecom companies.
Satellite	Satellite communication is mature and providers have a broad customer base. Satellite communications can be used to provide service where RSEs (for DSRC) and cellular are not available. The communications is lower-bandwidth and higher-latency than DSRC, and also there are challenges in providing "regional" information.	Satellite service providers are making progress in the CV area. These providers will continue to enhance their capability to provide traveler information to their customer base while collecting data from vehicles.
Wi-Fi	Wi-Fi is a mature, ubiquitous technology, and is cost-effective with high-bandwidth capabilities. Today, Wi-Fi can be used as both a probe and end connection technology. Security considerations are well understood with continually maturing solutions. However, a-priori knowledge of a Wi-Fi network for information dissemination is a challenge. Additionally, Wi-Fi utilizes a "handshake" process to establish communication, which is detrimental in a CV environment.	Wi-Fi access will continue to proliferate and operate in a crowded 2.4GHz /5GHz operating environment. Applications may emerge that use Wi-Fi to implement various V2X interactions (especially connectivity to backhaul systems in areas where traffic may be stopped—e.g., intersection). These apps may minimize a-priori concerns by pre-authorizing network names within the application environment.
Bluetooth and Low-Energy Bluetooth	Bluetooth is another mature, pervasive, and cost-effective technology used for both probe and reception. Bluetooth technology has implemented a number of service-level and device-level security measures, which require authorization and authentication before accepting data, making it a robust platform for communications. Bluetooth standards compliance is exceptionally high.	Future uncertainties over range as manufacturers embrace lower-power radio implementations. Discovery options for Bluetooth may differ for smartphones vs. in-vehicle navigation devices. Bluetooth will continue to operate in the crowded 2.4GHz spectrum.

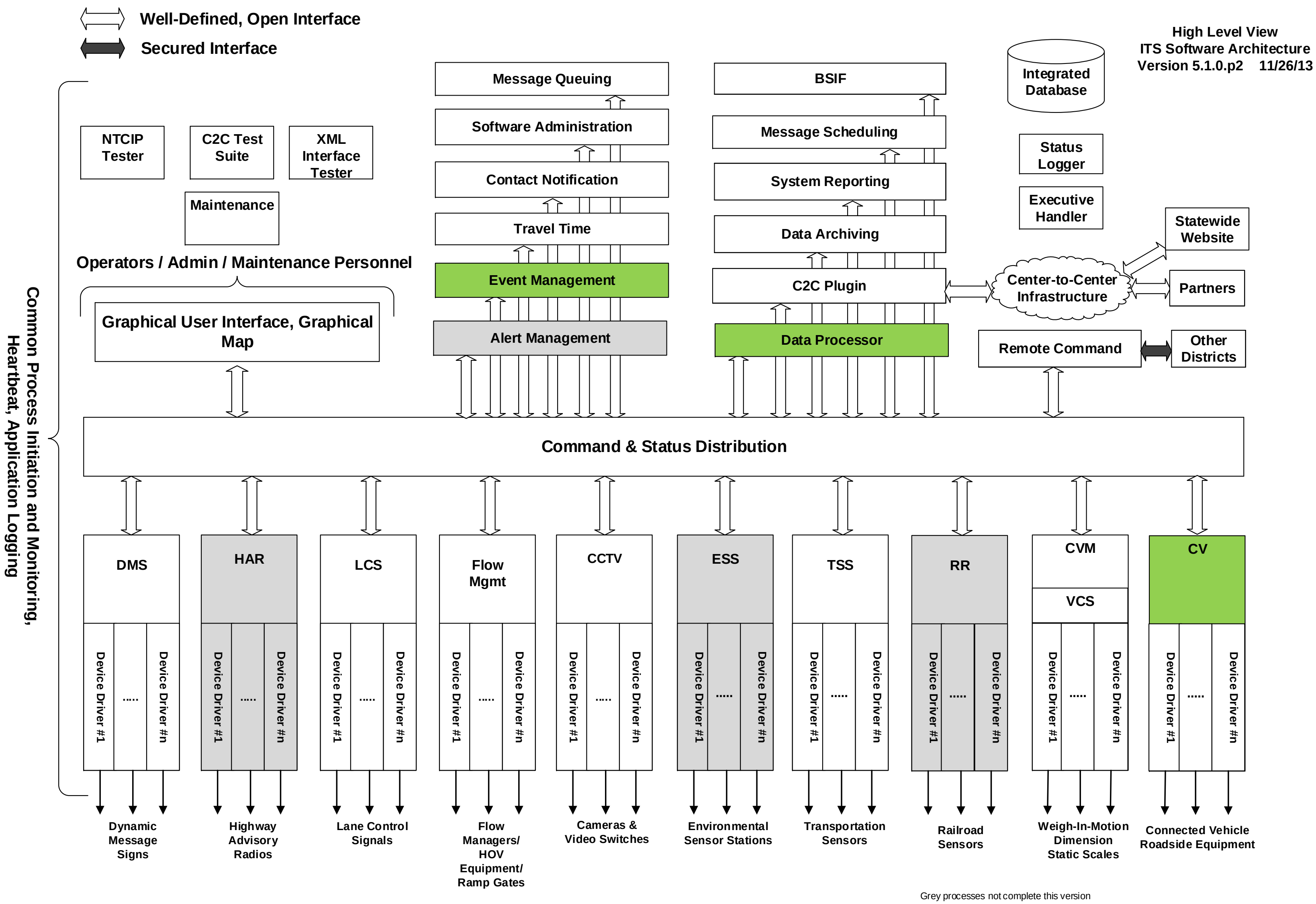
5.7 Deployment Strategies and Challenges

A wide-area deployment of CV technology can be a challenge, since it involves a number of stakeholders, like state agencies, metropolitan planning organizations (MPOs), cities, and counties. Following are a few of the issues involved in this process:

- Determining an appropriate deployment plan based on expected demand (CV population), hardware maturity, and CV application availability.
- Ensuring that regional and local entities have provided input into the plan and have buy-in throughout their organization.
- Include "data integration" activities in the deployment planning to provide local entities access to CV data.

Maintenance considerations for both CV hardware and software are critical to the long-term planning of a CV deployment. The National Connected Vehicle Field Infrastructure Footprint Analysis by the American Association of State Highway and Transportation Officials (AASHTO) estimates maintenance costs for CV hardware to be consistent with other Intelligent Transportation Systems (ITS) infrastructure, at about 1–2% of the installation costs, and that roadside equipment (RSE) devices may need to be replaced every 7 to 10 years. Staffing to support CV infrastructure day-to-day operations is highly dependent on the scale and complexity of a CV deployment, and what applications are actively supported, and would not include staffing requirements for the development of new CV applications.

Advanced Traffic Management Software (ATMS), such as TxDOT's Lonestar, will need to be integrated with CV functionality, similar to the integration performed on the Florida DOT's SunGuide ATMS system. This integration was accomplished through the creation of a CV subsystem/driver, which provides a means for V2I communications to and from an ATMS over a DSRC network. This existing code base can be leveraged by TxDOT through the creation of forms suitable for display within the Lonestar map interface and integration of the CV driver and subsystem into the Lonestar architecture. Most of this work would involve standardization of message sets between the CV driver/subsystem, and the Data Processing Algorithm and Event Management to process data to and from RSE, which in turn would transmit and receive data to and from CVs. Figure 5.1 illustrates this high-level architecture, with CV-related components in green.



Source: TxDOT ITS Architecture 6.0

Figure 5.1: Lonestar ATMS architecture with CV integration

Additional applications could also be implemented, using both cellular and DSRC communications mechanisms, in order to establish a CV communication infrastructure capable of demonstrating feasibility along Texas roadways for both technologies. This could provide some level of CV functionality to a larger population of vehicles, while enabling a framework for expansion as these particular technologies evolve.

5.7.1 Event Management

Event Management (EM) support for CV applications requires modification of existing message sets to standardize communication between the CV, and the Data Processing Algorithm and EM subsystems (as defined above). Once this is accomplished, existing functionality within Lonestar will provide appropriate communications to and from CV RSEs. CV events propagated through RSEs and sent through the Lonestar CV subsystem will create CV alarms. These alarms can then be processed programmatically and/or manually through the user interface as events created by EM, which in turn are distributed to appropriate subsystems to provide messages and/or alerts as applicable, such as dynamic message signs and highway advisory radios. These events can also be transmitted back through the CV system to targeted vehicles via DSRC in order to provide visual and/or audio alerts to drivers.

The following strategies are targeted CV applications that could use a CV subsystem within Lonestar to meet the current and future CV needs of TxDOT as well as those of commercial stakeholders.

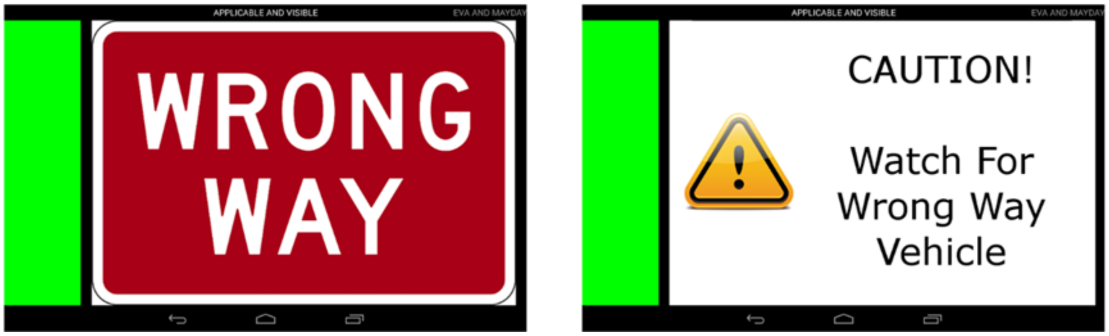
Mayday Alerts

Mayday alerts allow vehicles to generate messages requesting assistance such as 'Accident,' 'Flat Tire,' 'Stalled Vehicle,' etc. These messages can be propagated via other CVs until they are in range of an RSE, at which point they are relayed through the CV subsystem to the Lonestar ATMS for additional processing and generation of alarms. These alarms can in turn be used by the EM subsystem to manually or programmatically generate alerts that can be transmitted to interested parties as needed.

Wrong-Way Driver Notification

There are several potential implementations for a CV wrong-way driver warning system. One implementation utilizes an external wrong-way detection sensor as an input to trigger when a vehicle is detected traveling the wrong direction in a specific area. A process on an RSE that receives the wrong-way detection generates and broadcasts a warning message to all vehicles nearby. A second implementation utilizes a process on an RSE to monitor the basic safety messages broadcast from vehicles to identify vehicles traveling in the opposite direction of the defined roadway network. This requires that the roadway network, including intended direction of travel, be defined in the system and that the definition is accessible to the process on the RSE. When a vehicle is detected traveling against the defined flow of traffic, a warning is broadcast to all vehicles nearby with information about the vehicle, specifically its speed, heading, and location.

In both cases, vehicles receiving the message analyze the content to determine if it is applicable to them; i.e., they are approaching the vehicle that was detected, in which case a message is displayed to the driver indicating that they should exercise caution ahead and be aware of the vehicle traveling in the wrong direction. In addition, if there are police vehicles within range of the RSE, they will be notified regardless of their direction of travel. Wrong-Way Driver and Wrong-Way Driver Caution alerts are illustrated in Figure 5.2.



Source: SwRI WWD User Interface

Figure 5.2: Wrong-way driver warning and caution alerts

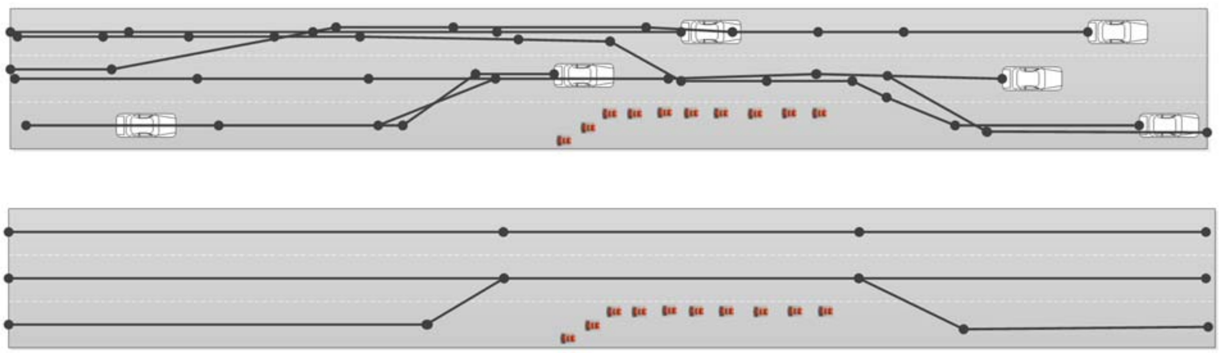
Spot Weather Warnings

Weather data can be processed by the Lonestar ATMS by leveraging existing Compass drivers as well as environmental sensor stations (ESS) sensor drivers. This data can be processed programmatically and/or manually via the EM subsystem described above in order to provide real-time spot weather messages and/or alerts as needed. These alerts can be provided to CV motorists via the CV subsystem through RSEs and connected DSRC-equipped vehicles as well as to non-CV users via dynamic message signs and highway advisory radios. Following are currently existing software drivers that can be integrated into Lonestar to provide this functionality:

- Compass
  - National Weather Service (NWS) Driver
    - Provides real-time xml feed of NWS alerts
    - Can be ported to ESS subsystem
- Lonestar
  - Vaisala Weather Sensor Driver
    - Provides weather data directly from sensor
    - Input to ESS for generation of weather related alarms
  - Visibility and Road Friction Sensor Drivers
    - Provides visibility data directly from sensor
    - Input to ESS for generation of weather related alarms

5.7.2 CV Lane Modeling for Event Detection

The Southwest Research Institute (SwRI) has developed a set of software tools that enable the passive collection of vehicle basic safety messages to be converted into a high-fidelity, lane-level model of the local roadway structure. These algorithms use the behavior of vehicles, as evidenced by their driven paths, to infer the details of lane structure, which have the potential to change due to a construction lane closure, a collision, or an obstruction caused by other debris. Once the lane-level map has been reduced to a minimum set of GPS points, it is shared back to the local vehicle population, and represents the most up-to-date information on the structure of the local lanes in near real-time. The process is fully decentralized and automatic, continually updating the model(s) as vehicles drive through an area. An example of a dynamically changing lane model is illustrated in Figure 5.3, where CVs traversing through the range of an RSE leave basic safety message "breadcrumbs" (top), which can be aggregated into a sparse-waypoint lane model (bottom). Lane model data can be integrated into the proposed CV subsystem, making it available to the Lonestar ATMS. Lane model data can be processed via the EM subsystem described above to provide real-time alerts as needed. Alerts can be generated for both system operators and drivers to indicate potential road obstructions based on a dynamic change in the expected lane configuration.



Source: SwRI Connected Vehicle Lane-level Modeling

Figure 5.3: Lane modeling application

5.7.3 RSE Management

TxDOT currently has three DSRC RSE units deployed along Interstate 410 in northwest San Antonio (Figure 5.4). To provide sufficient coverage for a functional urban CV system, additional RSEs would need to be installed on major highways and other travel corridors, such as IH 35 and US 281. The number of RSEs needed, and their locations, would need to be determined based on the desired coverage for an area, and the range of an RSE at a specific location, which is largely affected by line-of-sight characteristics (including elevation) and obstructions (like buildings).

Source: Google Earth

Figure 5.4: Current San Antonio RSE installation

5.7.4 Security Credentials Management System

In order to adhere to both current and future USDOT security standards, all TxDOT CV applications should be integrated with the federal Security Credentials Management System (SCMS) architecture[39] through an IPV6 infrastructure. All of the features provided by SCMS must be implemented by a software provider, including security bootstrap, certificate management, certificate revocation, and misbehavior reporting. Security credentials would be provided directly by USDOT and loaded onto RSEs by a traffic management entity like TxDOT.

5.7.5 Monitoring Health and Status of RSE

Once integrated into Lonestar, RSEs could be polled as CV devices using existing Lonestar functionality, thus allowing unresponsive devices to be recognized and targeted for automatic restart via the additional hard reset module. An example of a hard reset power module is illustrated below, and is similar to the device scheduled for installation in the San Antonio RSEs.

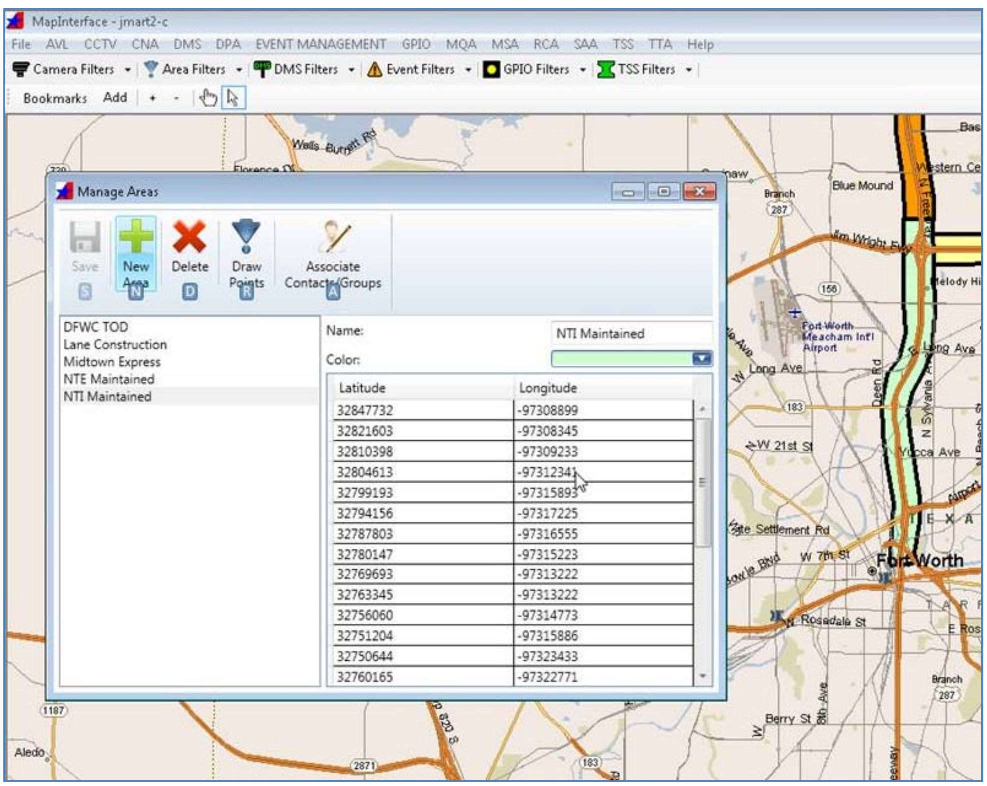
[39] See http://www.its.dot.gov/pilots/pdf/CVPilot_Webinar4_SCMSv2.pdf, pg 17-24, and http://www.iteris.com/cvria/html/applications/app63.html.

Source: http://www.controlbyweb.com/webrelay/

Figure 5.5: Hard reset relay module

5.7.6 Region Editor (Overheight and Wrong-Way)

Current proof-of-concept implementations of Overheight and Wrong-Way V2I CV functionality require manual configuration by plotting points on Google Earth and entering coordinates in a configuration file. This procedure is both time consuming and prone to user error. Production use of these applications is only feasible through the addition of an automated Region Editor tool for Overheight and Wrong-Way zone configurations. A Region Editor can be implemented leveraging existing Lonestar map interface code to provide familiar stand-alone and map interface modalities. An example of such an editing control is illustrated in Figure 5.6.



Source: SwRI Region Editor GUI

Figure 5.6: Map interface editor control

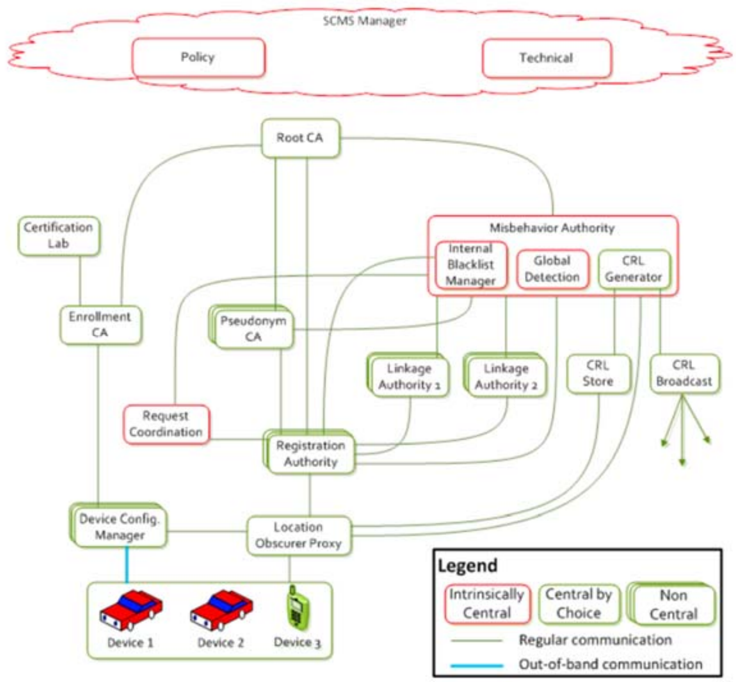
5.8 Benefits

Each of the items targeted for implementation will provide measureable benefits through current and future CV functionalities. The automated sign and inventory system would provide a detailed inventory for asset tracking in addition to generating data needed for the generation and display of virtual signage. Integrating a CV subsystem with Lonestar would enable leveraging of existing code and physical infrastructure to support CV applications while providing a scalable system capable of supporting future stakeholders as they become interested. Additional CV applications—including safety applications, event management, spot weather warnings, and CV lane management alerts—increase the visibility of CV capabilities and encourage use of this technology by other stakeholders. RSE management will extend the coverage area of DSRC radios while implementing a hard reset and monitoring solution will increase the stability and dependability of these devices. Implementation of an overheight and wrong-way region editor will provide an interface familiar to current Lonestar users capable of providing CV alerts to system operators as well as directly to CV drivers.

The deployment of additional CV-infrastructure support for both DSRC and cellular technologies in conjunction with the enhancement of software and integration with the Lonestar ATMS will provide additional CV functionalities for TMC operators using familiar tools. In particular, the integration of a new CV subsystem with Lonestar and EM will provide the ATMS with an additional set of data via the propagation of vehicle probe data. This data can be used to augment current functionality and will be available moving forward to support additional uses as they are identified. Newly implemented functionality will also provide benefits to CV drivers by providing a means to request assistance (mayday alerts) and alerting drivers to weather-related dangers and potential external dangers (safety applications, CV lane alerts). CV integration will also allow alerts to non-CV drivers through traditional means such as dynamic message signs. The expanded range provided by this infrastructure and the additional functionalities implemented should increase visibility of the CV program in general and thus encourage its use by additional shareholders.

5.8.1 Cybersecurity

NHTSA is leading the efforts to develop a comprehensive SCMS for CVs, and a recognized critical component of this architecture is the detection of anomalous behavior at a system level. Within the ITS domain, this is known as *global misbehavior detection* (GMD). Figure 5.8 depicts a high-level architecture model of the SCMS. GMD is a challenging problem because the global dynamics of a system comprising numerous interacting individuals is an emergent phenomenon.



Source: http://its.dot.gov/presentations/CV_PublicMeeting2013/PDF/Day1_LukucSecurity.pdf

Figure 5.7: NHTSA SCMS architecture (as of September 2013)

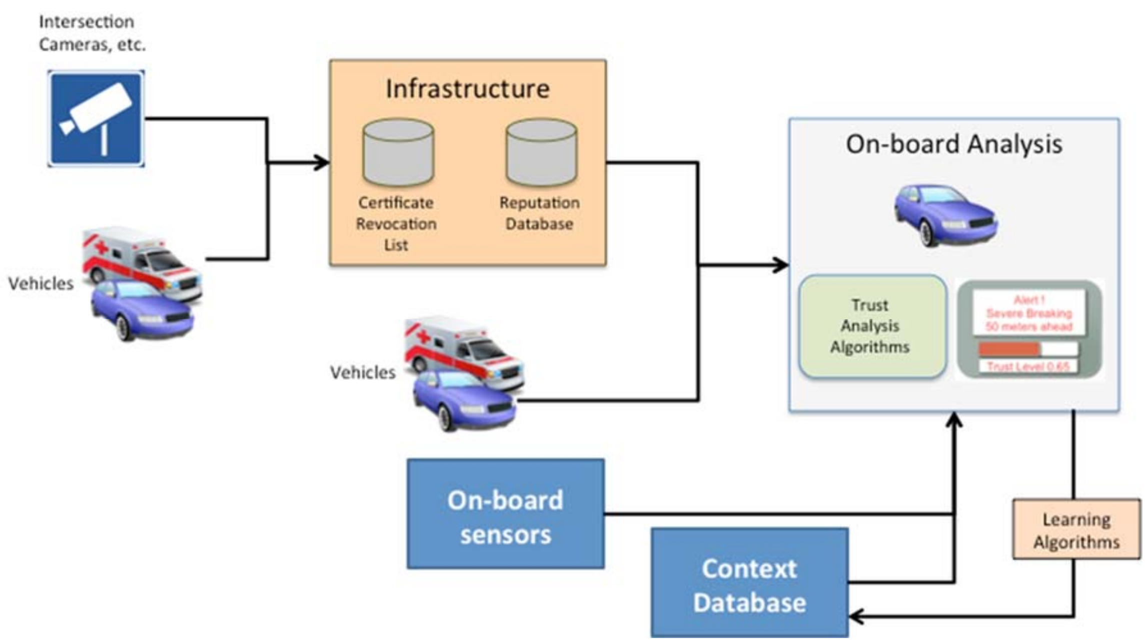
Increasing connectivity among vehicles in urban traffic systems provides opportunity for beneficial impacts such as congestion reduction; however, it also creates security risks with the potential for targeted disruption. Security algorithms, protocols and procedures must take into account the unique aspects of vehicle and highway systems. Security for a CV environment must go beyond message *authentication* to consider the broader issue of message *trust*, which is particularly important if the message could trigger a safety-critical response, potentially creating a risk to drivers and passengers. There are numerous scenarios in which false information inserted into a CV system may cause wide-spread system disruption. The USDOT Research and Innovation Technology Administration (RITA) recently published a series of reports describing a proposed public key infrastructure (PKI) approach for securing V2V and V2I communications (RITA, 2011 and RITA, 2012). A PKI system uses certificates to establish trust in communications. The sender digitally signs the message and attaches a certificate. The recipient uses the certificate to verify the sender's credentials, however this verification is accepted only if a trusted Certificate Authority issued the certificate. The advantage of this system is that it enables vehicles to trust each other regardless of whether they are near RSE.

The most difficult problem with the PKI approach is the distribution, management, and revocation of security certificates. In theory, a certificate will be revoked if it is used to "spoof" another device's identity or to send incorrect data caused either by equipment malfunction or a deliberate act. Periodically the Certificate Authority will issue a certificate revocation list that enables vehicles to detect when a message comes from a bad actor. Even with this brief description, it is clear that there are substantial technical problems in designing a PKI system for 250 million privately owned and operated vehicles with no central registration, licensing, or administrative authority. Further complicating the system, vehicles may be registered in one locale while connecting to ITS infrastructure in a different region, state, or country. Yet more complexity is added by privacy concerns that require message anonymity to deter tracking and monitoring of individual vehicles.

Multiple methods have been proposed for detecting bad actors, ranging from onboard hardware checks to global sampling of reports from multiple vehicles. For example, the OBE can compare ECU component identification to detect when it is installed in a different vehicle. At a local level, the OBE can check that its sensor data with incoming messages to check for consistency and plausibility. At a global level, the infrastructure can randomly collect messages from vehicles to determine if multiple messages contain certificates issues to the same OBE. Misuse detection is critical to the success of CVs and although there are numerous ideas, the work in this area is just beginning.

5.8.2 Methods for Improving Confidence in CV Messages

The proposed PKI approach is a good starting point for CV security; however, there remain gaps to prevent completely trusting a CV message simply because it was signed by a certificate. Similarly, there are multiple scenarios in which legitimate messages could lack authentication or be signed by an expired certificate. This problem is not necessarily true for messages from RSE, where tight control over equipment and certificates is possible, and will be expected. An entity such as TxDOT will need to take this into consideration when evaluating the deployment of CV devices onto their network, shown in Figure 5.9 as the “Infrastructure” box, and the connecting devices. Building strong security into the CV system will have costs, but not doing so will have even greater costs.



Source: SwRI Connected Vehicle Trust-based Security

Figure 5.8: Using trust factors to improve V2V message security

Data analytic methods are being developed at SwRI for the detection of anomalous behavior within a CV-enabled traffic system (GMD), and vehicle OEMs are actively working to detect cyber-attacks within the vehicle itself (local misbehavior detection). These detection methods will enable the development of mitigation strategies that can be deployed at multiple levels, from hardware and vehicle OEMs to traffic management entities like TxDOT.

5.8.3 Conclusions

The deployment of CV technology on Texas roadways has the potential to provide a number of benefits to individuals and society as a whole. However, without careful consideration of deployment strategies, including data management, cybersecurity, maintenance processes and costs, and usage demand and patterns, these benefits will not be realized. CV functionality will need to be integrated into the Lonestar ATMS to support the various infrastructure-based CV applications that are and will be available, as well as to provide a valuable source of real-time vehicle probe data to TxDOT from CV users within the range of installed RSEs.

A phased approach to the deployment of CV technology on Texas roadways is recommended, which will enable TxDOT to minimize the risk and cost of implementation, while also following trends in vehicle-based CV technology adoption. Research and development projects should also continue to be aggressively pursued by TxDOT, to understand the core and emerging technologies of CV and AV systems, including issues of legality, and how those systems can be integrated into the Lonestar ATMS.

5.9 B-C Analysis

5.9.1 Methodology

This report estimates the CAV strategy benefits and costs from the perspective of transportation system managers. The benefits for several of the strategies are reductions in crashes resulting from CV or AV use. Any operations benefit expected for implementing a particular strategy are mentioned in the B-C analysis discussion below for that strategy. Because of the limited data and models available for AV technologies, the research team cannot reasonably estimate operations benefits from simulation data for several of the strategies. Thus, predicted BCRs are given in lieu of estimated BCRs when applicable.

The BCRs were developed by quantifying the costs and benefits associated with implementing a strategy. Any construction or installation costs were assumed to be completed in Year 0, which represents the present time. The net present value of the cash flow was calculated using a set discount rate and project life. Because these strategies were being analyzed from a DOT's perspective, a standard discount rate of 5% was used. A project life of 40 years was used for each strategy. Because AV adoption is expected to occur over several decades, using a longer project life was appropriate. The formula used to obtain the BCR is presented below:

$$BCR = \frac{\sum_{t=0}^{T}\left(\frac{B_i}{(1+i)^t}\right)}{\sum_{t=0}^{T}\left(\frac{C_i}{(1+i)^t}\right)}$$

where B_i represents the benefits of the project in year t, C_i is project costs in year t, I is the discount rate, and T is the project life of the investment or strategy (e.g., T = 20 to 40 years). The resulting BCRs are discussed below for each strategy across three adoption levels: assuming 10%, 50%, and 90% of vehicles are instrumented and actively using the CAV technology. It is important to note that the benefits estimated are *potential* benefits instead of actual benefits, since these technologies have not yet been realized in the transportation network yet. When estimating the potential safety benefits for each market penetration scenario, the crash reduction rate for each is assumed using engineering judgment, unless otherwise noted.

5.9.2 Cooperative Intersection Collision Avoidance System

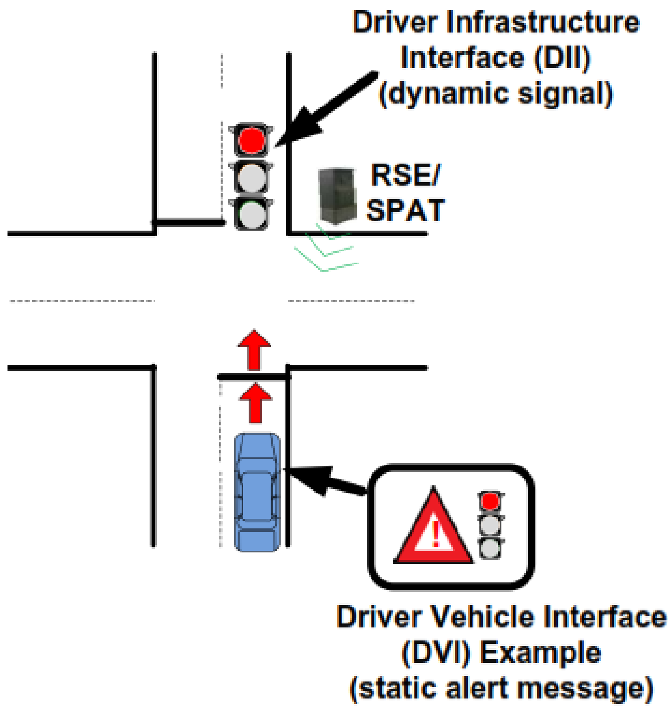
CICAS is a V2I strategy that is designed to reduce the frequency of collisions that occur at both signalized and stop-controlled intersections. Intersections that are equipped with CICAS technology warn vehicles via DSRC signal communications of an impending collision. There are several CICAS technologies that research centers are currently looking into. Because of the frequency of crashes that occur at roadway intersections, implementing CICAS can potentially reduce the amount of fatalities, injuries, and property damage occurring each year on roadways. These CICAS technologies have largely focused on improving safety of vehicle passengers at controlled intersections, but other applications include preventing fatalities and injuries caused by vehicles contacting pedestrians. The primary three CICAS technologies that address intersection safety are listed below:

- RLVW
- SSGA
- SSVW

The costs and benefits of using a RLVW system is developed separately from SSGA and SSVW because RLVW would be implemented at signalized intersections while the latter two would be implemented at stop-controlled intersections. It is important to note that it isn’t feasible to install CICAS technology at every intersection and that a reasonable recommendation would be to give preference to intersections with the highest crash frequencies. Information from the Crash Records Information System (CRIS), which is maintained by TxDOT, could be used to form criteria for which intersections should be given highest priority.

5.9.3 Red Light Violation Warning System

An RLVW system’s primary purpose is to alert CVs or AVs that a current trajectory will result in running a red light, thus allowing the CV’s driver or the AV itself to take preventive action. The vehicle that receives this data can pass this information to other AVs equipped with V2V tech so that those vehicles can make the proper adjustments as well. Figure 5.9 shows the visual configuration of RLVW at a typical intersection.



Source: Davis, 2013

Figure 5.9: RLVW configuration

The CAVs would receive the warning from the installed RSE, which, in the case of an RLVW application, would broadcast the traffic signal phase and timing information. The AV uses the information from that device to determine whether it will violate the red light (Davis, 2013). The CAV will adjust its speed to ensure that it will not run the light.

The cost of implementing an RLVW system at an intersection can be estimated by examining the components that make up the system. In TxDOT Project 0-6838, it was noted that while the DOT would not pay directly for the CAVs' onboard RLVW system, the DOT would need to pay for the RSE's hardware, installation, and maintenance costs. Equipment needed for a complete RSE includes sensors, DSRC radios, cameras, and power lines. Interviews with experts conducted in Project 0-6838 estimated the cost of purchasing CICAS technology for an intersection to be $10,000 to $20,000. Since the cost of CICAS technology is expected to decrease over time as familiarity with the technology is acquired, a conservative estimate of hardware and installation costs is $15,000 per intersection. Installation costs are expected to be similar to equipment costs, and a total estimated cost of upgrading an intersection with CICAS technology is estimated at $30,000. Annual maintenance costs for a CICAS system were estimated at $3,000. This cost estimate will be used when developing BCRs for RLVW, SSGA, and SSVW.

An RLVW system can address two of the pre-crash scenarios listed in Table 4.5 in Chapter 4: Running Red Light and Vehicle Turning Right at Signalized Junctions. To estimate the benefits of RLVW, a microscopic approach is taken by examining a single intersection in Austin that has historically had a relatively high crash frequency. The intersection of US 183 southbound frontage road and Martin Luther King Boulevard had the third-highest crash frequency of all intersections in Austin between the years 2008 and 2012, according to the 2012 Traffic Fatality Report published by the City of Austin. The average annual rate of crashes occurring at the intersection during this time period that resulted in fatalities was 0.2 per year, while the comparable rate for crashes resulting in injury was 12 per year.

Additionally, the average annual rate for property-damage only (PDO) crashes was eight per year. There is not much available numerical data concerning the potential impact of CICAS on safety as AV market adoption increases. Nonetheless, across the board crash reduction rates can be assumed to be 5%, 25%, and 45% at the 10%, 50%, and 90% AV market penetration levels. Cambridge Systematics estimated the average cost of a crash resulting in a fatality and an injury to be \$6,000,000 and \$126,000, respectively (Cambridge Systematics, 2011). According to the FHWA (1994), the average cost of a PDO crash is \$2,000 per crash in 1994 dollars. When converted to 2015 dollars, the average comprehensive cost of a PDO crash is \$2,784 per crash.

Using these values, the safety benefits per year are estimated at this intersection assuming an RLVW system is installed at this intersection using this formula:

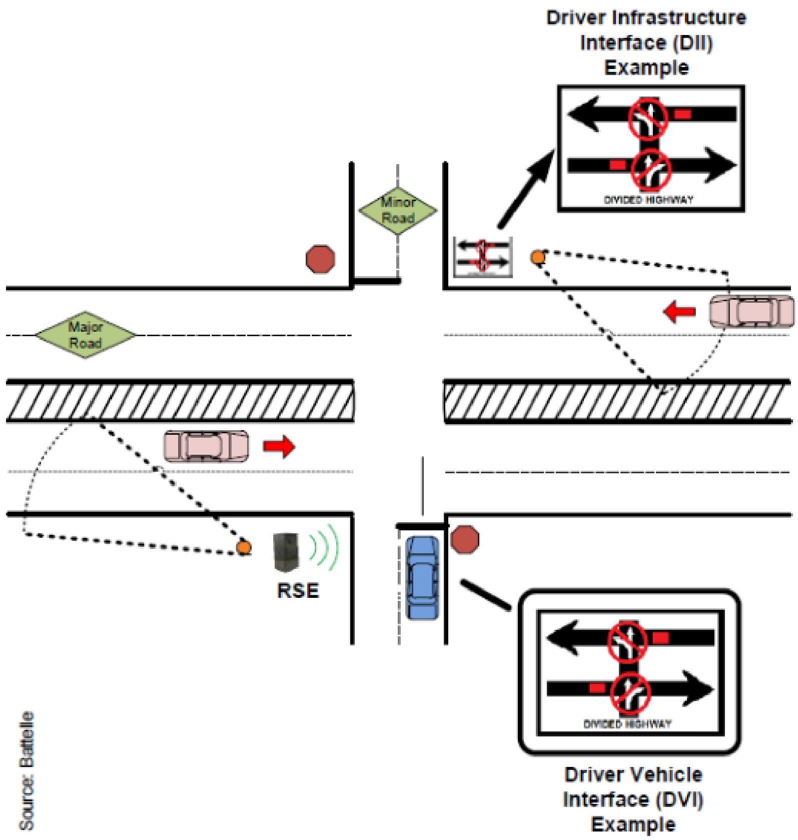
$$Safety\ Benefits\ in\ Year\ i\ = \sum \left(\#\ of\ \frac{crash\ type}{year}\right) * (Average\ cost\ of\ crash\ type) * r$$

where r is the assumed crash reduction rate.

The estimated BCRs at the 10%, 50%, and 90% AV market adoption rates are all greater than ten. These values obviously depend on the assumed crash rate, but at intersections with high crash frequencies that would be given first priority for RLVW system installation, the technology appears to have great potential for significant safety benefits. Being more conservative with the assumed crash rates would still yield B-C ratios significantly greater than one.

5.9.4 Stop Sign Gap Assist

A V2I strategy that helps improve safety at stop-controlled intersections is SSGA. The goal of SSGA is to help AVs determine if there is a satisfactory time gap for the vehicle to make a left turn, thru-movement, or right turn at an intersection (Davis, 2013). An RSE emits information about cross-traffic to approaching vehicles, and the AV can determine whether it needs to stop or if it can enter the intersection safely using this information. A simple SSGA installation is shown in Figure 5.10.



Source: Davis, 2013

Figure 5.10: SSGA configuration

As with an RLVW system, AVs must be equipped with DSRC capabilities for the SSGA to function properly. The costs of implementing SSGA at a stop-sign controlled intersection should be very similar to those of RLVW at a signalized intersection. Both systems require RSE, sensors, DSRC radios, cameras, and power lines. The estimated costs of equipment and installation are $15,000 per intersection, which comes out to a total of $30,000 per intersection with $3,000 of annual maintenance.

SSGA addresses two pre-crash scenarios: Left Turn Across Path/Opposite Direction (LTAP/OD) at Non-Signalized Junctions and Straight Crossing Paths at Non-Signalized Junctions. Chang et al. (2007) also estimated the comprehensive crash costs related to stop-controlled intersections to be $15 billion. Converting this estimate from year-2000 dollars to 2015 dollars results in a total of $20.93 billion, assuming the number of crashes remains constant. This estimate represents the maximum benefit that could be realized if future technology were to prevent all crashes related to maneuvering through a stop-controlled intersection (FHWA, 2015). To estimate a BCR, a standard stop-sign intersection that has average fatality, injury, and PDO crash rates of 0.1, 1, and 1 per year respectively is assumed. As with RLVW, we assume across-the-board crash reduction rates of 5%, 25%, and 45% at the 10%, 50%, and 90% AV market adoption levels, respectively. Using the estimated crash costs from Cambridge Systematics and the FHWA, the BCRs at the 10%, 50%, and 90% AV market penetration levels are estimated to be 7.67, 38.4, and 69.1, respectively These numbers obviously will vary depending on the crash frequency at the intersection and the assumed crash reduction rate. However, it is evident that even with relatively low assumed crash frequencies, high BCRs could be obtained at intersections with high crash frequencies.

5.9.5 Stop Sign Violation Warning

The RLVW equivalent for stop-controlled intersections is SSVW. This safety application helps CAVs approaching the intersection avoid crashes that result from running a stop sign. This strategy is set up similarly to the configuration depicted in Figure 5.10 for RLVW (with the exclusion of the traffic signal). AVs approaching the intersection would receive notification of the stop sign from the roadside device and determine whether it is at risk of running the stop sign, which will allow the AV to make the proper speed change. This information would also be communicated to approaching vehicles downstream using V2V technology. The cost estimates of implementing this strategy are assumed to be equal to the costs of utilizing other CICAS strategies discussed earlier.

SSVW is the key strategy that can prevent crashes related to the Running Stop Sign pre-crash scenario. The potential benefits that could be addressed by implementing SSVW at an intersection were estimated by Chang et al. (2007). The researchers' estimate when converted to 2015 dollars came out to $9.36 billion. When considering a more microscopic approach and given that costs associated with upgrading intersections with the appropriate hardware, it is easy to imagine that implementing this strategy at the most problematic stop-sign controlled intersections would be pursued first. It is important to note that crash severity at stop-sign controlled intersections could be alleviated by installing a signal. However, as the costs of CICAS technology decreases and assuming safety is the only warrant that justifies building a signal, it may be more cost effective to only install CICAS at the stop-sign intersection without a signal. As a result, BCRs should be predicted with the assumption that installing CICAS technology is cheaper than installing and maintaining a traffic signal at the intersection. The BCRs developed for SSGA are assumed to hold for SSVW since there is limited data available that separates how effective CICAS technology would prevent crashes that SSVW and SSGA can individually address. Thus, the B-C ratios for SSGA are assumed to hold for SSVW.

5.9.6 Clearer Lane Markings

At early stages of CAV development, the sensors that CAVs use to perceive other vehicles, the roadway surface, and other roadway objects must be able to detect and discern pavement lane markings. It is expected that high-fidelity maps in combination with a precise GPS (global positioning system) will allow CAVs to precisely track their location.in the future and render pavement markings as non-essential for safe CAV use. Until that point, it is important that the transportation agencies consistently maintain pavement markings to ensure that CAVs can detect them and perform necessary functions such as lane-keeping and stopping at stop lines. The sensor systems detect the lane markings and send a signal to the CAV of an impending lane departure so that the vehicle can make a course correction. Two major barriers to accurate lane marking detection are paint wear and inclement weather, such as severe rain or snow, which reduce retroreflectance. The latter barrier was demonstrated when self-driving prototype vehicles developed by KAIST failed to detect lane markings in wet conditions after successfully detecting them in dry conditions at the 2014 Future Automobile Technology Competition in South Korea. Advances in sensor technology are expected as CAV technologies mature, which will occur as they become available to the public and market adoption rates rise. Content-based navigation is being developed so that CAVs can use other objects such as light posts or other vehicles to help the car traverse the correct route in the absence of quality pavement markings. Nonetheless, maintaining lane markings will, to an extent, help maintain safe operations of AVs as these technologies are developed.

The introduction of CAVs will most likely require the Manual on Uniform Traffic Control Devices (MUTCD) to be updated to reflect higher maintained standards of striping retroreflectivity, which is the ability of a material to reflect light back to its source with minimum scattering. Because CAVs will need to detect markings at night and in wet conditions, a higher maintained retroreflectivity standard may need be adopted to accommodate AVs in those unfavorable conditions. The 2009 MUTCD edition (the most recent available) does not require a minimum retroreflectivity for marking paint but the FHWA may adopt such standards in a future edition. Thomas & Schloz (2001) highlights the four most common pavement materials and their pros and cons, which are listed in Table 5.5:

Table 5.5: Most common pavement materials

Material	Advantages	Disadvantages
Preformed Tape	- Easy to install - High durability	- High cost - Susceptible to chipping
Paint	- Relatively inexpensive - Performs well on pavement in poor condition	- Not as durable
Thermoplastic	- Durable - Higher retroreflectivity than paint	- Not very effective in high humidity - More difficult to install
Methyl Methacrylate	- Good visibility at night and in wet weather	- Health concerns (volatilization) - Not very effective in high humidity

Thomas and Schloz (2001) cite recent research as consistently showing that white markings have higher retroreflectivity than yellow markings, and that thermoplastic material is more retroreflective than paint. However, paint is less expensive, and reflectivity tends to vary by setting (e.g., urban versus rural).

Another important component of pavement markings that can be used to provide retroreflectance is raised pavement markers. The Texas Manual on Uniform Control Devices states that raised pavement markers can be used to supplement lane markings or as a substitute for missing or faded lane markings. Voronov et al. (n.d.) proposed that pavement markers installed 20 to 25 meters apart along a roadway to act as a "fail safe" in the case that pavement markings cannot be detected by an AV's sensors. These pavement markings lie slightly above the pavement surface, while reflecting light back to the vehicle and its sensors, and could be very useful during the early stages of AV development.

The FHWA estimates the cost of re-marking lanes at anywhere between $634/lane-mile to $17,160/lane-mile—based on varying levels of marking sophistication and whether it is surface-applied or inlaid. David Valdez of TxDOT's Maintenance Division shared pavement marking cost information with the project team, noting that TxDOT classifies pavement marking maintenance costs into four categories defined by roadway classification (which includes the annual average daily traffic, or AADT). The costs associated with TxDOT's desired level of maintenance for these four categories are listed here:

- Two-lane highways with AADT < 10,000 → $1,219/mile

- Multilane highways with AADT < 10,000 → \$2,483/mile
- Two-lane highways with AADT > 10,000 → \$1,828/mile
- Multilane highways with AADT > 10,000 → \$3,724/mile

This analysis uses these cost estimates provided by the maintenance division. Many TxDOT-maintained roads experience high AADT, which means pavement markings can wear quickly. Because of this, it is recommended that DOTs adopt standards that ensure sufficiently high retroflectivity in their pavement markings. As more information becomes available on sensor detection of lane markings—especially during rain, fog and other detection-equipment-limiting conditions—more research will be needed to develop standards for retroreflectivity.

Since BCRs gauge the potential benefits of strategies versus costs when budgets are limited, developing a BCR for a strategy like maintaining clear pavement markings may seem unnecessary. With the 50% AV and 90% AV market levels, technology is expected to have developed to a point at which AVs know their exact location at all times and do not need pavement markings to prevent issues like lane departure. As a result, it is assumed that at the 10% AV market penetration level, people are willing to pay (WTP) \$0.50/day for clear pavement markings. As technology develops and AV market share rises, the need for clearer pavement markings should decrease and it is assumed that WTP decreases to \$0.10/day. At the 90% AV market share, pavement markings will not be required and WTP is assumed to fall to \$0.01/day. The average vehicle occupancy nationwide was estimated in the 2009 National Household Travel Survey that was sponsored by the FHWA. Considering a two-mile-long road with AADT of 10,000 vehicles, and assuming an average vehicle occupancy of 1.67, we can estimate BCRs at all three market adoption levels. The economic benefits of maintaining pavement markings are estimated using the following formula.

$$Benefits\ in\ Year\ i = (AADT) * \left(1.5\ \frac{persons}{veh}\right) * (WTP) * (365\ \frac{days}{yr})$$

To be conservative, the maintenance costs for multilane striping for roads with AADT greater than 10,000 is used. Only maintenance costs are assumed in this analysis since potential CAV use on existing roads is being analyzed. The useful life of pavement markings will vary based on materials used, the road's level of service, geography, and various other factors (Migletz, 2001; Lertworawanich & Karoonsoontawong, 2012). Studies have shown service lives that range from several months to years, and the definition of service life may change if future reflectivity standards are adopted (Kopf, 2004; Zhang, 2010; Bowman, n.d.). To be conservative, the maintenance costs are counted 12 times each year over the 20-year project life. This assumes that maintenance is done on a monthly basis. At the 10% AV market adoption level, we get a BCR of greater than 10. A BCR of 4.18 is obtained at the 50% level, and a BCR of 0.42 for the 90% market rate. These values do depend on the AADT, the length of the road segment, and the WTP. If a busier road is selected, the BCR should be higher; on roads with less traffic, the BCR is expected to decrease.

5.9.7 Road Pricing

In a time where DOT budgets are limited and expanding capacity is not always a viable option, transportation demand management strategies are more frequently being considered as an alternative to expanding capacity. Though CAVs may be able to reduce headways in the long term, planners must be able to employ strategies that improve the level of service while incentivizing the purchase of CAVs, which will help improve their market penetration and more quickly realize the benefits of CAV use for Texans. One demand strategy that may be considered is road pricing, allowing the transportation agency to charge users of a system fees or tolls to minimize excess demand. Road pricing can be broken down into policies such as variable tolling, micro-tolling, and managed lane pricing. *Managed lane* pricing is a strategy that can be used to promote the use of CAVs and *variable tolling* refers to a tolling system in which different links on a network are tolled at variable prices depending on the link capacity. *Micro-tolling* refers to a tolling system in which the difference between the free-flow travel time and the current travel time on a link is monetized and applied to users of the link. Each of these strategies is described below, along with their predicted BCRs.

Variable Tolling

Variable tolls can be used to manage congestion on links. Users pay higher tolls during times of day when demand is higher and lower tolls when demand is low. This basic strategy is also referred to as *time-of-day pricing* if prices do not change instantaneously. *Congestion pricing* is another form of variable tolling in which road prices change as demand changes, with prices increasing as congestion increases. This tolling strategy is used to maintain a minimum operating level of service, and prices may fluctuate from day to day. Variable tolling can be used to promote carpooling, transit use, telecommuting, and working alternate time shifts, which can help alleviate congestion during peak hours. Though variable tolling remains an unpopular option with the public, the introduction of CAVs into the market may make this strategy more suitable due to the possible increase in total VMT. Research has shown that CAV use has the potential to increase total vehicles miles traveled on a network, which may be a result of new users (such as disabled persons or minors who were formerly unable to operate a vehicle), and also the increased mileage that shared AV fleets may produce when traveling unoccupied at various times of the day (Chen et al., 2016).

The costs of implementing variable pricing are largely dependent on location and configuration. Tolling schemes has historically required construction of tolling booths as well as labor and other resources to maintain the system (TTI, n.d.). To minimize labor costs, electronic tolling collection (ETC) is often employed (Persad et al., 2007). ETC systems require either in-road sensors or overhead video technology to monitor vehicles passing through toll checkpoints on a given route (Persad et al., 2007). The Texas Transportation Institute (TTI) reports that the cost of implementing ETC per lane can range from $100,000 to $200,000 (TTI, n.d.).

The benefits associated with variable tolling will also depend on the configuration, location, and the operations decisions of the system manager. TTI reports that a study using data from the ETC employed on the Carquinez Bridge near San Francisco reported a BCR of 40:1 over a 10-year period. To estimate the specific benefits of implementing variable tolling for a CAV fleet is impractical at this point because of the lack of simulation data. Especially in a state like Texas where non-tolled roads cannot be converted into tolled roads, extensive use of ETC would carry significant sunk costs that may not be justified unless system managers are given permission to toll roads with high volumes like IH 35.

Micro-Tolling

Micro-tolling refers to a tolling system in which all links (certain routes with specified length) on a network, including high-capacity corridors, arterials, and collectors, are tolled the monetary difference in time between the current travel time on the link and the free flow travel time. It is a novel concept in which the tolling system uses satellite data to constantly assess the travel times on each link, which allows advanced algorithms to calculate the optimal toll for each link that ultimately optimizes lane throughput. The toll assigned to each link is constantly updated in order to minimize delay experienced by vehicles in the system. TxDOT Project 0-6838 developed traffic models that showed that employing micro-tolling could reduce average travel times by up to 35% when compared to a system without tolling, and 17% when compared to modern tolling macro-models that have little real-world application. Despite these potential benefits, quantifying the costs of implementing a micro-tolling system is difficult. Common sense would suggest that micro-tolling strategies could be employed using existing tolling infrastructure, especially those facilities with ETC systems. Constantly monitoring the capacity and demand of each link, which is infeasible with current technology and required in existing macro-models, is not required for micro-tolling. Future V2I technology may make it possible to implement a tolling system that is much simpler and maximizes the usability of the micro-tolling system.

A BCR was estimated by considering a simulation of the downtown Austin network. This simulation was conducted using the cell-transition model. The network contains 546 intersections and 1247 links and was simulated during the AM peak period. In all, 62,836 trips were taken in this simulation. Tolls were assessed using RSEs installed on each link. It was assumed that all vehicles driving in the network have DSRC capabilities that allow them to communicate with RSEs, which assess the tolls electronically. The toll collections were assumed to be refunded to customers in this scenario to isolate the benefits of congestion reduction. Equipment and installation costs for each RSE were estimated at $4,000, with annual maintenance costs assumed to be 10% of total equipment and installation costs. Annual benefits were estimated by running two simulation scenarios: with and without micro-tolling. The average reduction in travel time was multiplied by the number of vehicles driving in the network during the simulation to obtain the total travel time savings (TTTS). The TTTS is multiplied by a mean value of travel time (VOTT) of $22/hour. The VOTT distribution for cars on the network was derived from the work of Lukasiewicz, Karpio, and Orlowski (2012). Each car's assigned VOTT determined which route it took to arrive at its destination. The economic benefit of time travel time savings during the AM peak was calculated to be $24,400. This benefit was also assumed to hold for the PM peak. For conservatism, only the benefits in the AM and PM peaks were considered. Additionally, these benefits were assumed to occur only on weekdays (261 days of the year). This brings the annual benefit to $12,736,800. Using a project life of 20 years, a BCR of 11.63 was obtained.

Managed Lanes

Managed lanes are dedicated lanes that restrict toll-free usage to users based on vehicle type, directional flow, or other restrictions. To help promote safety and the adoption of CAVs in future years, AV managed lanes could be implemented. Managed lanes would help separate conventional vehicles and AVs and reduce crash frequencies associated with driver error. TxDOT Project 0-6838 conducted a detailed B-C analysis of AV managed lanes. Sullivan et al. (2009) estimated the construction costs of building managed lanes like HOV or high-occupancy-toll lanes to be $1.9 million per mile. Operations and maintenance costs were assumed to be $10,000 per mile in that study (Sullivan et al., 2009). TxDOT Project 0-6838 developed BCRs of 3.03 and 1.28 for the 25% and 75% CAV market penetration levels, respectively. The benefits were estimated by examining current and planned HOV roadway segments. Using these results, a predicted BCR of greater than two for the 10% and 50% market penetration rates was assumed in this analysis.

For the 90% market penetration rate, a BCR of less than one was assumed, since the exclusivity of using the lane diminishes and collisions between conventional vehicles and AVs are less likely as conventional vehicle market share decreases.

5.9.8 Smart Intersections

A significant portion of the crashes on a network occur at intersections, as has been well documented. Additionally, standard intersections are a source of substantial delay for vehicles. The term "smart intersections" refers to a new, alternative type of intersection management system in which a first-come/first-served (FCFS) reservation-based system designates right-of-way to AVs and conventional vehicles, rather than relying on traffic signals (Dresner & Stone, 2004; Dresner & Stone, 2006; Fajardo et al., 2011; Li et al., 2013). Implementing such a system would require AVs to have DSRC to communicate with the RSE installed to manage the intersection. The RSE sends a signal to an approaching vehicle at the intersection, which informs the car whether or not it can proceed. If it cannot proceed because another car is traveling through the intersection, the device sends a signal to the approaching vehicle telling it to slow down and stop.

A conservative cost estimate of a smart intersection RSE is $5,000 per module, as noted in TxDOT Project 0-6838. Installation costs are assumed to be the same as the equipment costs. Operating and maintenance costs are assumed to be 10% of the installation and hardware costs. To estimate benefits, the results of traffic simulations conducted by Patel et al. (2016) are used. The researchers analyzed a network containing 216 links, 122 nodes, and 25 signals in the city of Austin. The demand on their network was 64,667 vehicles over a 4-hour time period. Assuming 100% demand, which is associated with higher levels of congestion, and also assuming that all the cars on the network are CAVs, travel time per vehicle increased by 4.3 minutes. This reduction occurred after theoretically converting all 25 signals to reservation-based signals. Since the headways assumed for AVs are smaller than those for HVs, the travel time per vehicle would also increase as the market penetration of CAVs decreases. This would result in this strategy having a BCR of less than zero at all three market penetration levels. Levin & Boyles (2016) showed that reservation policies could have positive operation benefits at a single intersection as CAV market penetration increases, but the results of Patel et al. (2016) clearly show that the current configuration of reservation-based intersection control will not reduce delay in a network of multiple smart intersections.

There is a notable limitation to the results of Patel et al. (2016): 0.5 sec headways were assumed for all autonomous vehicles in the network. This headway assumption is very optimistic and serves to significantly increase capacity. If the AV headway was assumed to be 1.0 sec, reservations would most likely increase total delay even further, especially at higher mixes of AVs and HVs. Nonetheless, though these estimates portray smart intersections as an unwise investment, it is possible that new research that improves how multiple reservation-based intersections would work together could help justify the adoption of these innovative intersections.

5.10 B-C Analysis Results

The B-C results are summarized in Table 5.6. These results rest upon many assumptions that must be made due to the lack of sufficient simulation and/or field data. If the estimated BCR exceeds 10, an explicit value was not stated because the BCRs rely on several assumptions that, if changed, would alter the BCRs considerably. The maintenance costs were assumed constant each year for all strategies evaluated. Additionally, occasional rehabilitation costs outside of annual maintenance costs were not considered. The BCRs presented in Table 5.6 are preliminary and should be updated when more simulation data becomes available. Additionally, the funding of field studies by the transportation managers that deploy the technologies discussed would be an excellent way to improve the parameter selection for the B-C analysis.

Table 5.6: Summary of B-C analysis

Strategy	Costs	BCRs		
		10% AV	50% AV	90% AV
Red Light Violation Warning System	• Hardware: $3,000 per intersection • Installation: $1,000 per intersection • Operations & Maintenance (O&M): $400 per intersection	>10	>10	>10
Stop Sign Gap Assist		>10	>10	>10
Stop Sign Violation Warning		>10	>10	>10
Clearer Lane Markings	Remarking: $3,724 per mile per year for multilane highways (per David Valdez of TxDOT Maintenance Division)	>10	4.18	0.42
Variable Tolling	Installation: $3,000 per RSE module installed, for a total of $12,000 per mile per lane (four RSEs for each lane-mile)	2.43		
Micro-Tolling	• Hardware: $3,000 per RSE module installed on each link • Installation: $1,000 per intersection on each link • O&M: $400 per RSE module on each link	>10		
Managed Lanes	• Construction: $1.9 million per mile (converting existing HOV lanes into CAV-only lanes) • O&M: $10,000 per lane-mile (Sullivan et al., 2009)	>2	>2	<1
Smart Intersections	• Installation: $5000 per module (one per intersection) • Equipment: $5000 per module • O&M: $500 per module	<0	<0	<0

Though it is impractical to estimate the BCRs of several of the strategies at this time, the predicted BCRs help provide a sense of the potential that several of the infrastructure strategies have, as summarized here.

- The CICAS technologies show excellent promise because RLVW, SSGA, and SSVW are all expected to improve safety by helping prevent crashes.
- Keeping pavement markings updated will be a critical strategy to employ on a consistent basis as CAV market share remains low, because on board technology must be able to detect pavement markings. AV sensors and high-fidelity mapping are currently

improving to the point at which inclement weather and faded pavement markings will not affect operations.

- Variable tolling remains a viable option in today's market, and that is expected to remain unchanged as CAVs are introduced into the market. However, this strategy will be a tough sell to the public as tolling remains unpopular.
- Implementing managed lanes would provide an incentive to the seller to purchase an AV, which would help society reap safety benefits from AV use sooner.
- Smart intersections may fundamentally change how intersections are operated, while rendering much of the current capital invested in traffic signals useless. RSE would begin to replace traffic poles and overhead mastheads. When a grid of smart intersections is optimized using future work to be completed on this innovative strategy, a significant reduction in control delay experienced at intersections is anticipated

5.11 Conclusions and Future Work

The purpose of this study was to identify key infrastructure strategies that would help prepare the transportation system for the transition to CAV use. Eight strategies were selected as possible strategies that a transportation manager could pursue as AV adoption nears. The B-C analysis provided BCRs for the eight strategies. Assumed values in the B-C analysis can be adjusted as better data (simulated and actual) become available. Based on the analysis and judgment, several of the strategies that BCRs were obtained for appear to be worthwhile (with BCRs > 1) at one or more different levels of AV market penetration/adoption and use. An RLVW system appears to be the most valuable strategy, with BCRs of greater than 10 at the 10%, 50%, and 90% market penetration levels. SSGA and SSVW also scored highly and showed long-term growth in value. Clearer lane markings and smart intersections also showed relatively high BCRs, but clearer lane markings diminish in value at higher market penetration. Finally, managed lanes yielded the lowest positive BCR, less than 2 at the 10% and 50% levels. At the 90% level, managed lanes are expected to not be a wise investment since most vehicles on the network will be CAVs and the benefits of separating conventional vehicles from CAVs will be diminished. Some strategies may best be gradually employed as AV adoption rates rise, while others, such as AV managed lanes, probably should be implemented early to help incentivize drivers to purchase CAVs, which offer many of their own benefits, well beyond the public agencies' investment and policy decisions (Fagnant and Kockelman 2014, 2015). Simulations of smart intersections will need to be optimized further before implementation is considered. The BCRs developed in this analysis are preliminary and should be recalculated once more simulation data can be provided that will allow for a more cohesive and rigorous analysis. These values will be used to help prepare final recommendations on the strategies that should be pursued to most effectively prepare for the introduction of AVs. These results will help transportation agencies plan for a horizon of several decades, with separate recommendations for the short, medium, and long term.

Chapter 6. Conclusions and Recommendations

Connected and automated vehicles (CAVs) are destined to change how the Texas transportation system operates. TxDOT is responsible for the nation's most extensive state-level network, and it is essential to explore the potential impacts of CAVs on the design, maintenance, and operation of the transportation system. Research into CAVs' mobility, environmental, legal, and safety implications for the state of Texas was conducted by UT Austin's Center for Transportation Research (CTR). This chapter outlines practice recommendations, emphasizing safety, to assist TxDOT in optimally planning for these new technologies using a holistic and qualitative approach.

Presently, the legal landscape for CAVs is one of much uncertainty and flexibility. Current Texas laws do not directly address such technologies; if this ambiguity remains unaddressed, it could hamper the state's ability to best prepare for CAV use. The National Highway Traffic Safety Administration (NHTSA) advocates adoption of laws that enable researchers to test CAV technologies while ensuring the safety of test subjects and roadway system users. Most observers, including NHTSA, agree that CAV research still needs development before driverless vehicles are ready for use by the public. In addition to setting the stage for advanced testing, the State must address questions concerning liability in the event of a crash involving CAV technologies like electronic stability control and lane-keeping assist. Existing crash responsibility law for conventional vehicles should be updated to reflect the increasing use of automation technologies.

A national survey and a Texas survey assessed the current state of public opinion towards existing and forthcoming CAV technologies. The U.S.-wide survey's fleet evolution results indicated that around 98% of the U.S. vehicle fleet is likely to have electronic stability control and connectivity by 2030. Long-term fleet evolution suggests that Level 4 AVs are likely to represent 25% to 87% of the U.S. light-duty vehicle fleet in 2045. Results suggest that 41% of Texans are not ready or willing to use shared autonomous vehicles (SAV) and only 7% hope to rely entirely on an SAV fleet, even at $1 per mile. AVs and SAVs are less likely to affect Texans' decisions about moving closer to or farther from the city center: about 81% indicated a desire to stay at their current location.

The current state of maturity of existing and developing CAV technologies was assessed and the recommendations and strategies can be found in Section 6.1 and 6.2 to provide recommendations for TxDOT to pursue in the short term, medium term, and long term. Identified strategies include pavement-marking updates, improving signage standards, modifying design manuals, shaping legislative policy on AVs, and establishing rules for SAV use, along with other options.

The transition from human-operated vehicle (HVs) to CAVs will not just bring benefits to the state of Texas but also present challenges that will need addressing. Several U.S. states have already taken steps in preparing for this paradigm change, and Texas will need to do the same. Listed below are strategies that the project team members feel are of importance to ushering in CAV use, organized into three flexible time periods: short term (next 5 years), medium term (5–15 years), and long term (15+ years). The associated descriptions should begin a discussion of the steps that Texas can take to best prepare the state transportation system for the onset of CAVs.

6.1 Recommended Strategies

6.1.1 Short-Term Strategies

In the short term (next 5 years), updating infrastructure should be prioritized to encourage safe use of CAV technologies that are currently on the market. Furthermore, shaping legislative policy in a proactive manner to better address questions surrounding the future testing and adoption of developing CAV technologies is essential for accelerating their deployment.

Road Markings

Several of the existing CAV technologies, such as lane departure warning, traffic jam assist, and truck platooning, require clear pavement markings to function properly. In the early stages of CAV development, pavement markings are expected to be used by initial CAVs for lane keeping. Pavement markings on roads wear with extensive road use and require regular maintenance to remain visible by drivers and detectable by the sensors used in the new technologies. It is crucial that TxDOT develop an organized strategy for periodically updating pavement markings and consistently inspecting markings on major freeways, arterials, and collectors in urban areas, where initial CAV deployment is expected to gain traction first. This will not only benefit drivers of vehicles with early smart sensing technologies, but will also provide TxDOT districts ample time to optimize their pavement marking update schedules in advance of CAV market penetration.

Signage Development for CAVs

CAVs will use sensors and visual cameras to detect signs and take appropriate action in reaction to a given sign. Current tests of self-driving vehicles have performed poorly in situations where uneven or non-detectable signs have rendered the vehicles inoperable (Sage, 2016). In cases of poor signage, more expensive and advanced sensors will be required to detect non-compliant signs or make the correct decision without the sign. TxDOT can improve the performance of CAVs by rehabilitating signage along roadways and updating signs to have better retroreflectance so that CAV sensors can more easily detect them. It will be helpful for TxDOT to establish standards for checking the retroreflectance and health of signs along roadways periodically.

Since signage is expected to play an important role in the operation of CAVs, updates to the Texas Manual on Uniform Control Devices (TMUTCD) should be made to require higher retroreflectance. Additionally, strategies that may possibly be employed for CAV use such as CAV-only lanes will require the addition of new sign designs to the TMUTCD and Texas Standard Highway Sign Design manual.

Shaping Legislative Policy on CAVs

There is a great deal of uncertainty regarding the current state of state and federal laws concerning CAV use. Various organizations and OEMs (original equipment manufacturers) are researching and developing CAV technologies, but there is little oversight on the extent to which CAV vehicles can be tested and operated for private use on Texas roadways. Because of TxDOT's status as the primary transportation agency in the state, the organization can play an important role in shaping the legislative policy on the testing and deployment of CAVs. Though taking no legislative action is a possible option, being proactive on shaping policy will help Texas reap the potential safety and operational benefits expected of CAVs to a greater extent and at a faster pace. Some of the legislative questions that TxDOT should urge the legislature to address include:

1) Setting standards for testing and development of CAVs
2) Legally defining the "operator" of a CAV
3) Establishing rules for intensive use of truck platooning
4) Addressing privacy and security questions stemming from CAV use
5) Answering liability questions that arise from CAV adoption
6) Advancing broader public goals in CAV innovation

6.1.2 Medium-Term Strategies

In the medium term (5–15 years), TxDOT should focus on strategies that will help increase CAV market penetration, which will help reap the expected benefits of their use sooner. Additionally, the agency should help form policies that regulate to an extent how CAVs operate in given conditions such as nighttime darkness or near construction zones.

Construction/Detours Methodology

It will be important to develop a plan for rerouting CAVs in the event of construction or other incidents that cause certain routes to close temporarily. Since CAVs will use mapping technology for navigation, integrating detour information into maps will be necessary for helping CAVs traverse the preferred alternate route. TxDOT should develop recommendations for which agency shall be responsible for communicating detour information to minimize delay and passenger dissatisfaction.

Lane Management

As CAV development increases and the state begins to reap the anticipated benefits of CAV use, lane management in the form of CAV-only lanes could potentially serve as a method of incentivizing the use of CAVs. In addition to speeding up travel for CAVs on roads with a CAV-only lane, this form of lane management would help alleviate the effects of HVs and CAVs mixing on the same routes. Additionally, removing CAVs from lanes with normal access using lane management will improve travel times for conventional vehicles slightly.

Nighttime Road Rules

Nighttime driving conditions can be dramatically different from daylight driving conditions. To ensure safe nighttime driving conditions, TxDOT and other agencies responsible for vehicle operation and registration (the Texas Department of Public Safety, Texas Department of Motor Vehicles, and local law enforcement agencies) should explore the development of rules requiring CAV vehicles to operate headlamps with a minimum amount of power so that HVs can detect CAVs on the road properly.

SAV Integration

As CAV technologies develop, SAVs could emerge as an alternative to private CAV use or ownership. This potential shift to SAVs would be similar in form to the rise in popularity of transportation network companies such as Lyft and Uber. It will be important for the state to develop guidelines for SAV operation in order to promote a safe and efficient SAV system. SAVs will most likely begin and gain prominence in urban areas; coordinating with local municipalities on expectations for SAV regulation is an important step in developing a uniform standard that each local SAV system can adhere to. Though SAVs would operate as Level 4 CAVs, which are not anticipated to be used significantly until the long term, planning in advance for SAV use as a major mode of travel will make the transition to such a system easier.

Developing and Enforcing Regulations for Empty Driving

It is important to note that SAV use is expected to increase total system vehicle miles traveled (VMT), as SAVs will need to reposition themselves to meet demand, often without any passengers. Though heavy SAV use could reduce personal vehicle ownership, increased VMT resulting from new SAV trips, with and without passengers, could have a negative impact on sustainability. Additionally, the availability of Level 4 CAVs could incentivize personal vehicle trips without a passenger. As an example, someone could hypothetically use their personal driverless vehicle to deliver a package. More demand, which can lead to higher levels of congestion, could increase emissions resulting from CAV use. TxDOT should advocate for legislation that prohibits or decentivizes empty driving in order to minimize the negative externalities of such personal vehicle trips. Furthermore, the state could also consider regulations of SAV repositioning to ensure that a designated level of sustainability could be achieved.

Roadway Design Amendments (within TxDOT Manuals)

As CAVs increase in market penetration, requirements in the TxDOT Roadway Design Manual (and potentially other manuals as well) will need consistent updates to reflect the ongoing changes in vehicle technology. Certain requirements that may change include those for sight distance, curve radii, cross-sectional slopes, and other elements of geometric design. Ideally this should be completed in concurrence with changes in the AASHTO Roadway Design Manual. However, even if AASHTO does not make significant changes, TxDOT should still consider updating any pertinent in-house manuals to ensure that Texans can benefit from CAVs, and that it has mechanisms in place to ensure the safety of these vehicles and passengers.

Tolling and Demand Management

Though Texas has historically not used demand management policies extensively, the expected CAV-induced VMT will make demand management strategies a viable alternative to examine in the coming years. Since augmenting current tolling facilities with elements such as gantries and cameras will necessitate high capital costs, new methods of charging users for the marginal cost of their travel should be explored. One of these new methods is known as micro-tolling or delta-tolling, which requires all CAV drivers or passengers on a given link to pay the monetary difference between the free-flow travel time and the current travel time. Depending on the users' value of travel time, each vehicle will find the optimal route that minimizes their toll en route from origin to destination. This system could potentially be implemented using relatively low capital cost and even lower marginal costs. Micro-tolling, which incentivizes drivers to be more conscious of their trip path in a local network, is anticipated to provide only modest improvements, as micro-tolling is expected to be implemented on collectors and local roads rather than freeways and major arterials. The potential adoption of traditional tolling schemes that utilize alternative technologies such as GPS (global positioning system) tracking and RFID (radio-frequency identification) tags should be explored. Traditional schemes are more feasible for longer corridors with higher levels of congestion.

6.1.3 Long-Term Strategies

Long-term strategies (15+ years) should center on the extensive use of CAVs and other equipment that operates without human assistance, in stark contrast to today's HV-dominated car market. New design standards for construction and maintenance that reflect the increasing use of CAVs should be developed. Smart intersection management will be needed. This will include renegotiation of current intersection management agreements where on- and off-system networks meet as well as development of options for micro-tolling to ensure intersections can optimize throughput. Initial CAV use is expected to begin in urban areas, and then branch out to rural areas after market penetration reaches high levels in areas with large populations. Long-term strategies should focus on helping rural areas make the transition to CAV use.

Construction and Maintenance Design

Improving construction and maintenance design standards to adapt to CAV use will help the state complete its transition to a transportation network with mostly AVs. Because the vehicles used for construction and maintenance are anticipated to become driverless as well, new regulations addressing this change should be developed to maintain safe and orderly operations. Additions or changes to the specifications for the design of streets, highways, and bridges should be made to reflect changes in vehicle technology.

Rural Signage and Rural Road Design

CAV use is expected to begin in urban areas and then gradually move to rural areas once market penetration increases. As with urban areas, rural areas will need proper signage to help improve detection of the signs by CAV sensors. Furthermore, updates made to the roadway design manual should be considered when designing new roads and redesigning and performing maintenance on existing rural roads. Further updates may be considered to help address road conditions typical of rural roads.

Smart Intersections

Smart intersections are an alternative intersection management strategy that relies on a first-come first-serve tile-based reservation system. In other words, CAVs could traverse through an intersection by reserving a space in the intersection in advance. If another CAV attempts to reserve the spot that was already reserved at that given point of time, it will have to wait for the other CAV to proceed first. Researchers developing the schemata for this form of intersection management are looking to improve this system to a state in which arterial progression can be maintained and the delay caused by HVs at smart intersections is minimized. TxDOT will at some stage want to review the intersection agreements it has with many jurisdictions to update these to include the roles, responsibilities, and duties of the jurisdictional parties.

6.2 Best-Practice Recommendations for TxDOT in Deployment of CAVs in Texas

6.2.1 Short-Term Practices

1) The Department should establish a department-wide working group to:
   a) Coordinate and provide to the Legislature technical advice as well as recommendations for legislative policy making and changes or additions to the Texas Transportation Code and Texas Administrative Code applicable to CAVs;
   b) Oversee continuing research and testing needed to assess the technically feasible and economically reasonable steps for TxDOT to pursue over time, with emphasis on those actions that will encourage early CAV market penetration;
   c) Create and update annually a CAV policy statement and plan;
   d) Create and update annually a policy statement and plan for non-CAV vehicle support and operations during the transition to CAVs; and
   e) Coordinate CAV issues with AASHTO, other states, Transportation Research Board (TRB) committees, the Texas Department of Motor Vehicles, and the Texas Department of Public Safety.
2) The Traffic Operations Division (TRF), in coordination with other divisions, the districts, and other stakeholders, should establish and lead a team to:
   a) Oversee research and testing on additional or changed traffic control devices and signage that will enhance the operations of CAVs;
   b) Coordinate with industry in the short term on basic items in the MUTCD that are proving challenging in CAV development and deployment, such as sensor-compatible lane striping, road buttons, and machine-readable signage;
   c) Monitor and oversee development of cooperative intersection collision avoidance system technology and assist in test deployments on Texas highways and major arterial roads; and
   d) Monitor cooperative-adaptive cruise control and emergency stop device deployment and assess what steps TxDOT will need to take to assist in extending and translating this technology into throughput, such as improved platooning on trunk routes.
3) The Transportation Planning and Programming (TPP) Division, in coordination with other divisions, the districts, and other stakeholders, should establish and lead a team to:
   a) Develop and continuously maintain a working plan for facilitating early adaptors of CAV technology, in particular the freight and public transportation industries;
   b) Identify and begin planning with MPOs for the impacts of expected additional VMT driven by CAV adoption, particularly for assessing impacts on conformity demonstrations in non-attainment areas of the state;
   c) Begin assessment for and development of a series of TxDOT-recommended VMT management and control incentives for responding to the likely CAV-induced VMT increases; and
   d) In coordination with the Public Transportation Division (PTN), begin to monitor and assess the impacts of SAVs on the department.

6.2.2 Mid-Term Practices

1) The Department's department-wide working group should continue to:
   a) Create and update annually the CAV policy statement and plan;
   b) Create and update annually the plan for non-CAV vehicle support and operations during the transition to CAVs;
   c) Coordinate CAV issues with AASHTO, other states, TRB committees, the Texas Department of Motor Vehicles, and the Texas Department of Public Safety; and
   d) Coordinate and provide to the Legislature technical advice as well as recommendations for legislative policy making and changes or additions to the Texas Transportation Code and Texas Administrative Code.
2) The TRF Division, in coordination with other divisions, the districts, and other stakeholders, should:
   a) Continue research and testing for CAV-enabled smart intersections, expanding from off-road test facilities to actual intersections;
   b) Initiate research and testing for CAV-appropriate lane management operations, initially for platooning and CAV-only lanes;
   c) Expand CAV control device research and testing specific to construction zone, detour, and nighttime operations; and
   d) In cooperation with the engineering design divisions and the Maintenance Division (MNT), begin updating the various TxDOT manuals that will be impacted by CAVs.
3) The TPP Division, in coordination with other divisions, the districts, and other stakeholders, should:
   a) Research, test, and recommend incentives (for example, micro-tolling, time of day operations restrictions, etc.) for the control of congestion as well as increased VMT induced by CAVs;
   b) In coordination with PTN and local governments, assess the impact of AVs in public transportation operations, leading to recommendations appropriate to the Department's goal of congestion relief; and
   c) Begin research and testing of area-wide traffic demand management operations made possible by CAV technology.

6.2.3 Long-Term Practices

1) TxDOT's department-wide working group should continue to:
   a) Create and update annually the CAV policy statement and plan;
   b) Create and update annually the plan for non-CAV vehicle support and operations during the transition to CAVs;
   c) Coordinate CAV issues with AASHTO, other states, TRB committees, the Texas Department of Motor Vehicles, and the Texas Department of Public Safety; and
   d) Coordinate and provide to the Legislature technical advice as well as recommendations for legislative policy making and changes or additions to the Texas Transportation Code and Texas Administrative Code.

2) TRF and TPP should continue steps needed to identify the optimal traffic demand management strategies that are economically feasible and environmentally compliant, giving particular thought to centralized and automated allocation of routing and timing, as well as required use of SAVs operated to minimize VMT.
3) TRF, in coordination with the other engineering design divisions (Design Division, Bridge Division) and MNT, should research, test, and ultimately adopt changes to the department manuals optimized for CAV/SAV operations.
4) The engineering design divisions should research, test, and ultimately adopt roadway design elements that allow high-speed, but safe, CAV roadway operations in rural and uncongested suburban areas.
5) Finally, TPP, in coordination with TRF, PTN, and the engineering design divisions, should develop and recommend a series of options to the TxDOT administration and Texas Transportation Commission for aggressive traffic demand management in the major metro areas and along congested trunk routes.

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Appendix A. U.S. Survey

qualtrics

Start

Adoption of Self-driving and Connected Vehicle Technologies

UT Austin Internal Review Board # 2014-09-0078

Dear Respondent,

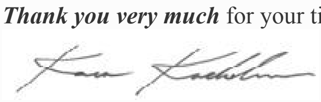
The Center for Transportation Research at **The University of Texas at Austin** is conducting a research study to explore preferences for and adoption of emerging self-driving and connected vehicle technologies and related traffic management strategies.

Self-driving vehicles and connected vehicles are new technologies with strong potential to improve traffic safety and mobility, and reduce emissions. Policymakers and transportation system planners need to assess how quickly such technologies will be adopted in order to develop optimal policies and strategies for traffic operations and management.

- The survey will take approximately **20-25 minutes** to complete.
- The survey will ask questions about you, your household's current vehicle inventory (example, odometer reading and average miles traveled per year), your future vehicle preferences, and preference for various self-driving and connected vehicle technologies.
- Your individual responses are **CONFIDENTIAL**. No names or other identifying information will be used in preparing the data for analysis.
- There are no risks involved in participation in this study and no direct benefits.
- **Your input and opinions** are **VERY IMPORTANT**, since it is critical that a variety of perspectives be represented in this survey.

If you have any questions or comments about this study, please feel free to contact me personally at kkockelm@mail.utexas.edu or (512) 471-0210. If you have any questions about your rights as a research participant, please contact the Office of Research Support by phone at (512) 471-8871 or email at orsc@uts.cc.utexas.edu. Your completion of the survey indicates your willingness to participate in the study.

Thank you very much for your time and cooperation.



Dr. Kara Kockelman
Professor of Transportation Engineering & Faculty Sponsor
www.caee.utexas.edu/prof/kockelman

Section 1- Current and Past Vehicles

Please TAKE YOUR TIME on this survey. There are many novel questions in this survey that require careful reading and thoughtful answers. Those completing the survey in less than 15 minutes are unlikely to have read many questions.

SECTION 1: CURRENT AND PAST VEHICLES

1. Does your household **currently own or lease** one or more vehicles?

Note: Household includes all persons who occupy a housing unit, such as a house, an apartment, a mobile home, a group of rooms or a single room. The occupants may be a single family, one person living alone, two or more families living together or any other group of related or unrelated persons who share living arrangements.

- Yes
- No

2. In order to forecast future vehicle ownership patterns and use, we need to know your **household's current vehicle ownership**. Please indicate the following for each of the vehicles used by your **household.**

	Make	Model (Example: Camry)	Fuel type	Year of manufacture	Year of acquisition	Current odometer reading (in miles) (Example: 15000)	Is this vehicle leased?	Bought new?	Odometer reading (in miles) at the time of acquisition (Example: 100)
Vehicle 1									
Vehicle 2									
Vehicle 3									
Vehicle 4									
Vehicle 5									
Vehicle 6									

3. Did you or anyone in your household **sell, donate, scrap, lose** (to a crash or other accident) or otherwise let go of a vehicle in the past **5 years**?

- Yes
- No

4. What vehicles have you or anyone in your household **sell, donate, scrap, lose** (to a crash or other accident) or otherwise let go of a vehicle in the past **5 years**?

	Make	Model	Fuel type	Year of manufacture	Year of acquisition	Odometer reading (in miles) at the time of	Last year of vehicle	Odometer reading (in miles) at the time you **sold,**

						acquisition	ownership	lost or given it away
		(Example: Camry)				(Example: 100)		(Example: 15000)
Vehicle 1	▼		▼	▼	▼		▼	
Vehicle 2	▼		▼	▼	▼		▼	
Vehicle 3	▼		▼	▼	▼		▼	
Vehicle 4	▼		▼	▼	▼		▼	
Vehicle 5	▼		▼	▼	▼		▼	
Vehicle 6	▼		▼	▼	▼		▼	

Section 2 - Consumer Vehicle Choice and preference for automation technologies

Survey Completion
0% 100%
10%

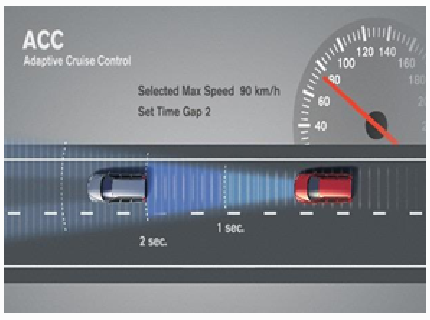
SECTION 2: PREFERENCE FOR VEHICLES AND SELF-DRIVING TECHNOLOGIES

Please read carefully before moving forward.
The National Highway Traffic Safety Administration (NHTSA) has defined five technology levels for vehicle automation technology. Levels 0 through 2 encompass technology that is commercially available today; Level 3 and Level 4 are emerging. These levels are defined as follows:

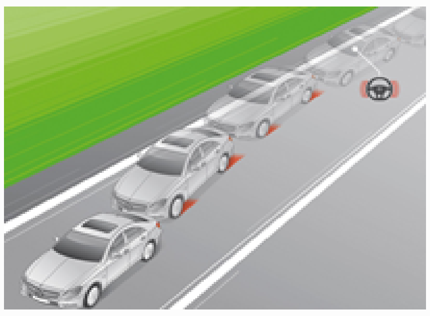
Currently Available Technologies for Consumers:

*No-Automation (**Level 0**):* The driver is completely responsible for the primary vehicle controls – braking, steering, throttle, and motive power – at all times.

*Function-specific Automation (**Level 1**):* Automation at this level involves one or more specific control functions. **Examples** include electronic stability control or pre-charged brakes, where the vehicle automatically assists with braking to enable the driver to regain control of the vehicle or stop faster than possible by acting alone. Other examples include adaptive cruise control (the ability of a vehicle to adjust its speed while in cruise control to maintain a safe following distance from a vehicle in front of it) and lane centering assistance (automatically adjusts the vehicle's steering angle away from a detected lane marker if a driver begins to wander out of his/her lane).



Adaptive Cruise Control


Lane Centering Assistance

*Combined Function Automation (**Level 2**):* This level involves automation of at least two primary control functions designed to work in unison to relieve the driver's control of those functions. **Examples** include combination of adaptive cruise control and lane centering assistance.

Emerging Technologies:

*Limited Self-Driving Automation (**Level 3**):* Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic and environmental conditions. This technology allows the driver to rely heavily on the vehicle to monitor for changes in those conditions, which may require transitioning back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time (example: 3 to 5 seconds). For example, the vehicle may be able to drive itself in low-speed environments or on freeways in good weather, but would need to transition to human control if inclement weather is encountered, or when turning onto higher-speed surface streets"


Level 3 Self-driving Vehicle

*Full Self-Driving Automation (**Level 4**):* The vehicle is designed to perform all driving functions for the entire trip. This design anticipates that the driver will provide destination or navigation input, but is not expected to be available for vehicle control at any time during the trip.


Level 4 Self-driving Vehicle

1. Which ONE of the following **decisions** are you and your household members considering at this time for the **next 12 months**?

- ○ We are planning on **selling one or more** vehicles.
- ○ We are planning on **replacing (selling and buying) one or more** vehicles.
- ○ We are planning on **buying one or more** vehicles.
- ○ We are **not** planning on **buying another vehicle**, but after learning about **automation and connected vehicle technologies** from this survey, I am planning on **adding** these technologies to one or more of our current vehicle(s) (assuming that these technologies can be added to used/existing vehicles).
- ○ We do not intend to take any above action.
- ○ Other (please specify):

2. Would you buy a **new or used vehicle**?

- I would buy a **new** vehicle.
- I would buy a **used** vehicle.
- I **do not know** whether the purchased vehicle would be new or used.

3. **How many vehicle(s)** do you plan to buy in next 12 months?

- 1
- 2
- 3
- 4
- 5 or more (please specify):

4. How much money do you plan to spend on the **next vehicle your household acquires**? If you plan to purchase **2 or more vehicles**, choose the maximum amount that you plan to spend on the **most expensive vehicle** and **answer the following questions for the same vehicle**.

Note: If you chose to "**buy and add automation technologies**", please **do not include** your budget **for adding** automation technologies.

- Less than $10,000
- $10,000 to $19,999
- $20,000 to $29,999
- $30,000 to $39,999
- $40,000 to $49,999
- $50,000 to $59,999
- More than $60,000

5. **How much ADDITIONAL money** would you be willing to pay for adding the following automation technologies (on top of your conventional [Level 1] car price) to your **next** vehicle?

	ADDITIONAL money you expect to pay
Combined Function Automation **(Level 2)**	▼
Limited Self-driving **(Level 3)**	▼
Full Automation **(Level 4)**	▼

6. What is the **desirable fuel economy** (under city driving conditions) of your household's **next vehicle?** (Please keep in mind the price your household want to spend on the next vehicle purchase.)

- **Less than 10** miles per gallon
- **10** to **14** miles per gallon
- **15** to **19** miles per gallon
- **19** to **24** miles per gallon
- **25** to **29** miles per gallon
- **30** to **34** miles per gallon
- **35** to **39** miles per gallon
- **40** to **44** miles per gallon
- **45** to **49** miles per gallon
- **50 or more** miles per gallon

7. What **size of vehicle** are you planning to buy? (Please keep in mind the price you want to spend on the next vehicle purchase.)

- **Mini-compact car** (Example: Smart Fortwo)
- **Subcompact car** (Examples: Ford Fiesta and Kia Rio)
- **Compact car** (Examples: Hyundai Elantra, Honda Civic, Toyota Corolla, and Volkswagen Golf)
- **Mid-size car** (Examples: Chrysler 200, Ford Fusion, Audi A4, and BMW 3 Series)
- **Large cars** (Examples: Chevrolet Impala, Lincoln MKZ, Jaguar XF, and Toyota Avalon)
- **Minivan** (Examples: Ford C-Max, Toyota Sienna, and Fiat 500L)
- **Cargo van** (Examples: Chevrolet Express 1500 Cargo, Honda CR-V, and Ford Transit)
- **Passenger van** (Examples: Chevrolet Express 1500 Passenger and Ford E350 Wagon)
- **Small sport utility vehicle** (Examples: Jeep Compass, Jeep Wrangler, and Honda CR-V)
- **Standard sport utility vehicle** (Examples: Audi Q5, Jeep Cherokee, and Ford Explorer)
- **Small pickup truck** (Examples: Chevrolet Colorado and Toyota Tacoma)

Standard pick-up truck (Examples: Ford F-150, Chevrolet Silverado, and Nissan Titan)

8. Which of the following **vehicle brands** (make) do you **plan to buy or lease in the next 12 months**? (Please keep in mind the price you want to spend on the next vehicle purchase.)

Vehicle Brand	

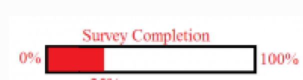
9. Please indicate the **make, model, year of acquisition, and year of manufacturer** for any vehicles you are presently considering selling.

	Make	Model (Example: Camry)	Year of acquisition	Year of manufacture
Vehicle 1				
Vehicle 2				
Vehicle 3				
Vehicle 4				
Vehicle 5				
Vehicle 6				

10. **How much money** would you be willing to pay for adding the following automation technologies (on top of your conventional [Level 1] car price) for your **current** vehicle?

	Money you expect to pay
Combined Function Automation **(Level 2)**	
Limited Self-driving **(Level 3)**	
Full Automation **(Level 4)**	

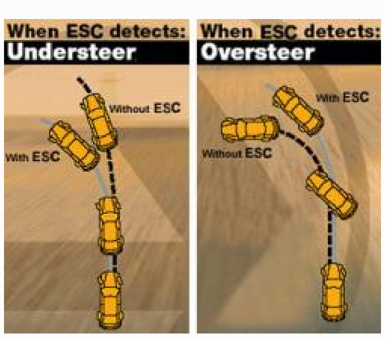
Section 3 – Willingness to Pay for Specific Automation Technologies



SECTION 3: WILLINGNESS TO PAY FOR SPECIFIC AUTOMATION TECHNOLOGIES

Note: This section will ask about your willingness to pay for various technologies. Current costs (and future estimated costs) for each technology are provided for illustration purposes.

1. **Electronic Stability Control:** When an extreme maneuver is attempted by the driver that nears or exceeds the traction limit of the vehicle, the vehicle will apply brakes to individual tires to maximize the driver's chances of keeping the vehicle under control.



Does one of your household's current vehicle presently have **Electronic Stability Control**?

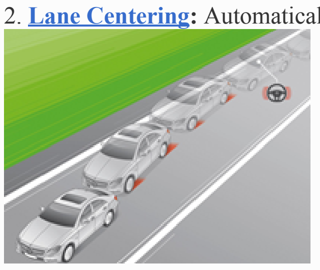
- Yes
- No

Electronic Stability Control prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$100
Price after 5 years	$70
Price after 10 years	$50

- Less than $60
- $60 to $79
- $80 to $119
- $120 to $149
- $150 to $200
- I **will not pay anything** to add **Electronic Stability Control**.

2. **Lane Centering:** Automatically correct the vehicle's heading if a driver begins to wander out of his/her lane.



Does one of your household's current vehicle presently have **Lane Centering**?

- Yes
- No

Lane Centering prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$950
Price after 5 years	$670
Price after 10 years	$480

- Less than $100
- $100 to $199
- $200 to $299
- $300 to $399
- $400 to $499
- $500 to $599
- $600 to $699
- $700 to $799
- $800 to $899
- $900 to $999
- $1,000 to $1,200
- I **will not pay anything** to add **Lane-Centering**.

3. **Left Turn Assist:** This feature will warn a driver attempting to turn left if there is an approaching vehicle traveling towards the driver's turn path.

Does one of your household's current vehicle presently have **Left Turn Assist**?

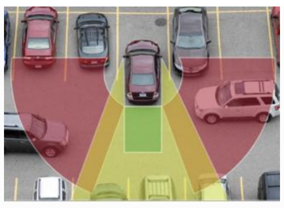
- Yes
- No

Left Turn Assist prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$450
Price after 5 years	$320
Price after 10 years	$230

- Less than $100
- $100 to $199
- $200 to $299
- $300 to $399
- $400 to $499
- $500 to $699
- $700 to $1,000
- I **will not pay anything** to add **Left Turn Assist**.

4. **Cross-Traffic Sensor:** This feature monitors up to a 120 degree angle at the rear of the vehicle to detect if there is cross-traffic when a driver is attempting to back out of a parking space.



Does one of your household’s current vehicle presently have **Cross-Traffic Sensor?**

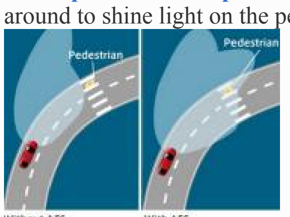
- Yes
- No

Cross-Traffic Sensor prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$550
Price after 5 years	$380
Price after 10 years	$270

- Less than $100
- $100 to $199
- $200 to $299
- $300 to $399
- $400 to $499
- $500 to $599
- $600 to $699
- $700 to $1,000
- I **will not pay anything** to add **Cross-Traffic Sensor**.

5. **Adaptive Headlamps:** The vehicle can detect the level of lighting and will turn on the headlights when a threshold is breached. It can also detect pedestrians (and swivel its main beams around to shine light on the pedestrians or other nearby moving objects).



Does one of your household’s current vehicle presently have **Adaptive Headlamps**?

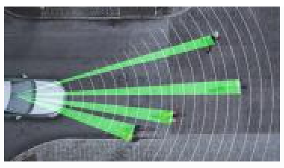
- Yes
- No

Adaptive Headlamps prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature t,o your household current vehicle or next vehicle purchase?

Current Price	$1,000
Price after 5 years	$700
Price after 10 years	$500

- Less than $150
- $150 to $249
- $250 to $349
- $350 to $449
- $450 to $549
- $550 to $649
- $650 to $749
- $750 to $849
- $850 to $949
- $950 to $1,049
- $1,050 to $1,249
- $1,250 to $1,500
- I **will not pay anything** to add **Adaptive Headlamps**.

6. **Pedestrian Detection:** Detect and notify a driver about nearby pedestrians. If the driver does not take action to avoid a crash, vehicle will stop, using its automated braking feature.



Does one of your household's current vehicle presently have **Pedestrian Detection**?

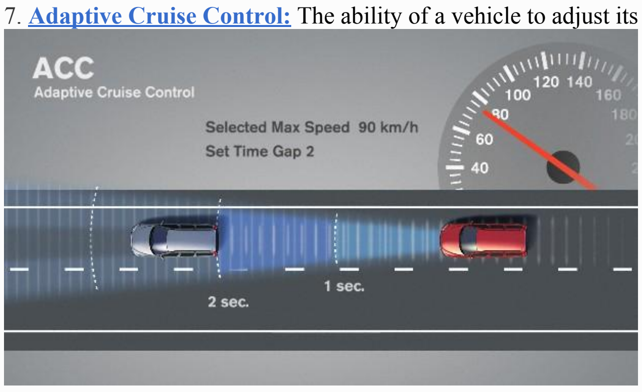
- Yes
- No

Pedestrian Detection prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$450
Price after 5 years	$320
Price after 10 years	$230

- Less than $100
- $100 to $199
- $200 to $299
- $300 to $399
- $400 to $499
- $500 to $699
- $700 to $1,000
- I **will not pay anything** to add **Pedestrian Detection**.

7. **Adaptive Cruise Control:** The ability of a vehicle to adjust its speed to ensure a safe (or minimum) distance from lead vehicles.



Does one of your household's current vehicle presently have **Adaptive Cruise Control**?

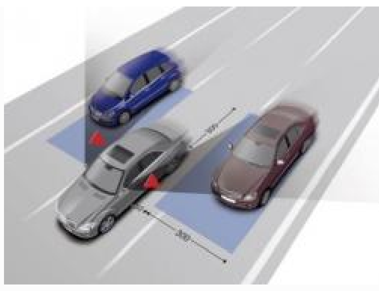
- Yes
- No

Adaptive Cruise Control prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$400
Price after 5 years	$280
Price after 10 years	$200

- Less than $50
- $50 to $149
- $150 to $249
- $250 to $349
- $350 to $449
- $450 to $699
- $700 to $1,000
- I **will not pay anything** to add **Adaptive Cruise Control**.

8. **Blind-spot Monitoring:** An indicator will warn the driver if a car is detected in its blind spot.



Does one of your household's current vehicle presently have **Blind Spot Monitoring**?

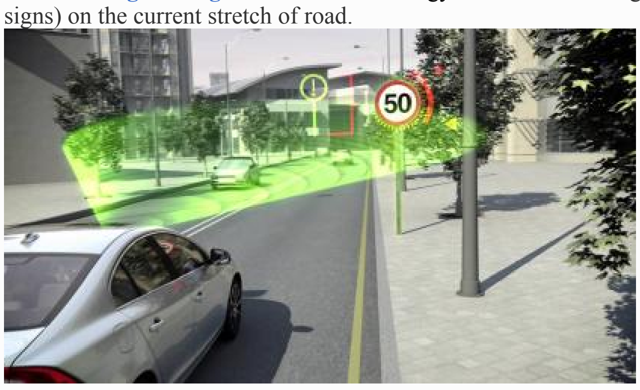
- Yes
- No

Blind Spot Monitoring prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$400
Price after 5 years	$280
Price after 10 years	$200

- Less than $50
- $50 to $149
- $150 to $249
- $250 to $349
- $350 to $449
- $450 to $699
- $700 to $1,000
- I **will not pay anything** to add **Blind Spot Monitoring**.

9. **Traffic Sign Recognition:** This technology will detect road signs and notify the driver about driving restrictions (examples: no overtaking, construction zone, speed limit zone, and stop signs) on the current stretch of road.



Does one of your household's current vehicle presently have **Traffic Sign Recognition?**

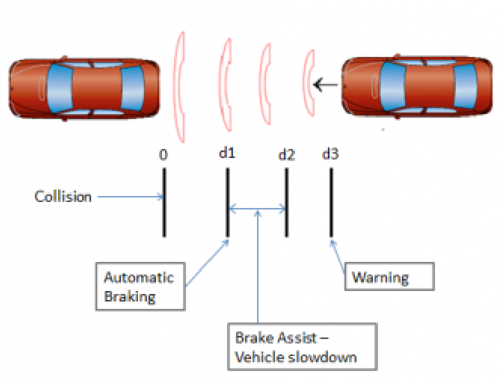
- Yes
- No

Traffic Sign Recognition prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$450
Price after 5 years	$320
Price after 10 years	$230

- Less than $100
- $100 to $199
- $200 to $299
- $300 to $399
- $400 to $499
- $500 to $699
- $700 to $1,000
- I **will not pay anything** to add **Traffic Sign Recognition**.

10. **Emergency Automatic Braking:** After detecting an obstacle on the road, if the driver does not react within a reasonable time frame, the vehicle will automatically apply the brakes.



Does one of your household's current vehicle presently have **Emergency Automatic Braking**?

- Yes
- No

Emergency Automatic Braking prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$450
Price after 5 years	$320
Price after 10 years	$230

- Less than $100
- $100 to $199
- $200 to $299
- $300 to $399
- $400 to $499
- $500 to $699
- $700 to $1,000
- I **will not pay anything** to add **Emergency Automatic Braking**.

11. Please **indicate your interest** in the following technologies.

Note: If you forget the function of any technology, please click on it to see the associated image. If you would like to see a description of these technologies, please **click here.**

	Very Interested	Slightly Interested	Not Interested
Electronic Stability Control	○	○	○
Lane Centering	○	○	○
Left Turn Assist	○	○	○
Cross-Traffic Sensor	○	○	○
Adaptive Headlamps	○	○	○
Pedestrian Detection	○	○	○
Adaptive Cruise Control	○	○	○
Blind-spot Monitoring	○	○	○
Traffic Sign Recognition	○	○	○
Emergency Automatic Braking	○	○	○

12. **Limited Self-Driving (Level 3)**: This technology will enable the driver to give full control of all safety-critical functions to vehicle under certain traffic or environmental conditions, but still requires transitioning back to driver control in many situations.

Limited Self-Driving (Level 3) prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$15,000
Price after 5 years	$10,500
Price after 10 years	$7,500

- Less than $2,000
- $2,000 to $3,999
- $4,000 to $5,999
-

$6,000 to $7,999
- $8,000 to $9,999
- $10,000 to $11,999
- $12,000 to $13,999
- $14,000 to $15,999
- $16,000 to $17,999
- $18,000 to $21,000
- I **will not pay anything** to add **Limited Self-Driving (Level 3)**.

13. **Self-Parking Valet System** **(Level 3):** Enables park a vehicle itself within the immediately adjacent parking lot.

Self-Parking Valet System prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$2,000
Price after 5 years	$1,400
Price after 10 years	$1,000

- Less than $250
- $250 to $749
- $750 to $1,249
- $1,250 to $1,749
- $1,750 to $2,249
- $2,250 to $2,749
- $2,750 to $3,000
- I **will not pay anything** to add **Self-Parking Valet System**.

14. **Full Automation** **(Level 4)**: The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Driver is not expected to be available for control at any time during the trip and thus can perform other activities (like working, reading, and sleeping).

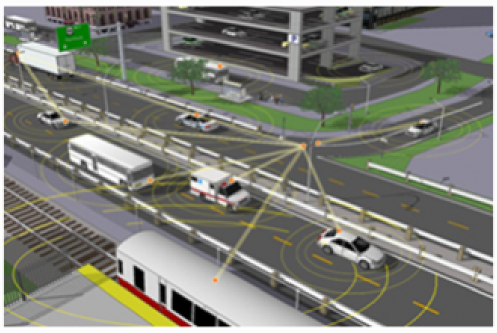
Full Automation (Level 4) prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$40,000
Price after 5 years	$28,000
Price after 10 years	$20,000

- Less than $2,000
- $2,000 to $5,999
- $6,000 to $9,999
- $10,000 to $13,999
- $14,000 to $17,999
- $18,000 to $21,999
- $22,000 to $25,999
- $26,000 to $29,999
- $30,000 to $33,999
- $34,000 to $37,999
- $38,000 to $41,999
- $42,000 to $45,999
- $46,000 to $50,000
- I **will not pay anything** to add **Full Automation (Level 4)**.

15. Connectivity may be added to an existing vehicle using one's smartphone plus additional equipment, such as dedicated short range communications [DSRC] technology and inertial sensors. Time-sensitive alerts to the driver could be audible sounds (like a message to "slow down" when congestion is forming up ahead or the roadway is deemed slippery), while more complex information may be relayed in text format (like real-time travel times to one's destination).

National Highway Traffic Safety Administration (NHTSA) recently announced an advanced notice for proposed rulemaking related to vehicle-to-vehicle communication technology for light-duty vehicles. Connected vehicles are equipped with technology enabling them to **"talk" to nearby vehicles and infrastructure** (traffic signal control boxes). This technology can be used for a variety of purposes, such as sharing information about nearby moving objects, roadway conditions, slowing vehicles, and better routes. Connected vehicles have the potential to increase roadway safety by reducing the number of crashes caused by human error.

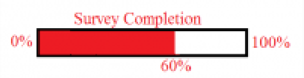


Vehicle Connectivity prices are likely to fall over time as shown below. **How much** are you **willing to pay** to add this feature to your household current vehicle or next vehicle purchase?

Current Price	$200
Price after 5 years	$140
Price after 10 years	$100

- Less than $25
- $25 to $74
- $75 to $124
- $125 to $174
- $175 to $224
- $225 to $274
- $275 to $400
- I **will not pay anything** to add **Vehicle Connectivity** .

Section 4 – Opinions



SECTION 4: OPINIONS

1. Do you **agree or disagree** with the following statements about car driving?

	Strongly Agree	Slightly Agree	Neutral	Slightly Disagree	Strongly Disagree
I believe that I am a **very good driver** myself.	○	○	○	○	○
I think self-driving vehicles will drive **more safely** than my driving.	○	○	○	○	○
Driving a car is something I **enjoy**.	○	○	○	○	○
In the case of a new technology, I generally **tend to wait** if it proves itself (based on user reviews, for example) before purchasing.	○	○	○	○	○

2. Do you agree or disagree about the following statements?

	Strongly Agree	Slightly Agree	Neutral	Slightly Disagree	Strongly Disagree
Self-driving vehicles are a **useful advance** in transportation.	○	○	○	○	○
The idea of self-driving vehicles is **not realistic**. Conventional vehicles will be the standard for the next 40 years.	○	○	○	○	○
Self-driving vehicles will be a **regular mode** of transport **in 15 years**.	○	○	○	○	○
Self-driving vehicles **scare** me.	○	○	○	○	○
I have **waited a long time** for self-driving vehicles.	○	○	○	○	○
I **do not think** that self-driving vehicles will function **reliably**.	○	○	○	○	○
I would be **comfortable sending** my self-driving car out on an errand knowing that I am liable if it gets into an accident.	○	○	○	○	○

3. Which **sources** would you **trust** to develop Level 4 self-driving vehicles? (Please check all that apply.)

- ☐ Technology companies (Examples: Google, Apple, Microsoft, and Samsung)
- ☐ Mass-market vehicle manufacturers (Examples: Toyota and Ford)

- ☐ Luxury vehicle manufacturers (Examples: BMW and Mercedes)
- ☐ Other (please specify) ______

4. How comfortable would you be in allowing your vehicle to **transmit information** (about its position and direction of travel, for example) to…?

	Very Comfortable	Slightly Comfortable	Neutral	Slightly Uncomfortable	Very Uncomfortable
Surrounding vehicles	○	○	○	○	○
Vehicle manufacturers	○	○	○	○	○
Insurance companies	○	○	○	○	○
Transportation planners	○	○	○	○	○
Toll operators	○	○	○	○	○

SECTION 5: TRAVEL CHARACTERISTICS

SECTION 5: TRAVEL CHARACTERISTICS

1. Which of the following is your **primary means of travel** for the following activities? (Please select one means of travel for each activity.)

	Walk	Bicycle	Drive Alone	Drive with Others	Bus	Not applicable
Work Trips (either home to workplace or workplace to home)	○	○	○	○	○	○
School Trips (to & from your own school or your child's school)	○	○	○	○	○	○
Shopping Trips	○	○	○	○	○	○
Personal Business Trips (Examples: gym & doctors' appointments)	○	○	○	○	○	○
Social/Recreational Trips (Examples: dining out & visiting friends)	○	○	○	○	○	○
Other Trips (Examples: daycare & computer repair)	○	○	○	○	○	○

2. **How many ROUND trips** did you make for the following **purposes** in the **last 7 days?**

	0 trips	1-2 trips	3-4 trips	5-6 trips	7-8 trips	9 or more trips
Work Trips (either home to workplace or workplace to home)	○	○	○	○	○	○
School Trips (to & from your own school or your child's school)	○	○	○	○	○	○
Shopping Trips	○	○	○	○	○	○
Personal Business Trips (Examples: gym & doctors' appointments)	○	○	○	○	○	○
Social/Recreational Trips (Examples: dining out & visiting friends)	○	○	○	○	○	○
Other Trips (Examples: daycare & computer repair)	○	○	○	○	○	○

3. What is the **one-way** distance of the following locations **from your home**?

	Less than 1 mile	1-3 miles	3-5 miles	5-10 miles	10-15 miles	More than 15 miles
Grocery store (one you visit most)	○	○	○	○	○	○
Bus or Rail stop	○	○	○	○	○	○
Airport	○	○	○	○	○	○
City's downtown	○	○	○	○	○	○

4. If my vehicle could be set to self-driving or manual driving when making each trip, I think I would **set it to SELF-DRIVING when** I am making…. (Please check all that apply.)

- ☐ All types of trips
- ☐ A work trip
- ☐ A school trip
- ☐ A shopping trip
- ☐ A personal business trip (Examples: gym and doctors' appointments)
- ☐ A social or recreational trip
- ☐ I would not use self-driving vehicle.

5. Please answer the following questions about **your long-distance travel** (where the one-way trip distance is at least 50 miles) over the **past 3 months**. (**Please skip** this question if you **did not make** any such trip.)

	Origin (Example: Austin)	Destination (Example: New York City)	Primary mode of travel	Trip type	Number of times you made this trip (in the past 3 months)
1			▼	▼	▼
2			▼	▼	▼

3					
4					
5					
6					
7					
8					
9					
10					

6. Assuming I own a vehicle that can drive itself, I believe I will put it on **self-drive mode** when I am making trips…. (Please check all that apply).

- Between 50 and 100 miles
- Between 100 and 500 miles
- Over 500 miles.
- I will **not use** self-driving vehicles for any such long-distance travel.

7. How many MORE **long distance trips (one-way trips *over 50 miles*)** do you think you will make each month (on average) if you have a fully self-driving vehicle?

8. **How many miles** do you estimate you **traveled in a car or truck over the last year**? (This may be your own vehicle, plus miles in a rental car, and miles in anyone else's passenger vehicle over the past 365 days.)

- less than 3,000 miles
- 3,000 to 5,999 miles
- 6,000 to 8,999 miles
- 9,000 to 11,999 miles
- 12,000 to 14,999 miles
- 15,000 to 17,999 miles
- 18,000 to 20,999 miles
- 21,000 or more miles

9. Do you have, or have you ever had, **any disability** that prevents you from manually driving a vehicle? (Please check all that apply.)

- No disability
- Vision impairment
- Mobility issues
- Cognitive disorder
- Other (please specify):

SECTION 6: DEMOGRAPHICS

SECTION 6: DEMOGRAPHICS

1. Including yourself, **how many people** live in your **household**? (Please do not include anyone who usually lives somewhere else or is just visiting, such as a college student away at school.)

- 1
- 2
- 3
- 4
- 5 or more (please specify):

2. Including yourself, **how many workers** usually live in your **household**? (Please include all the persons in your household who get paid for working full-time, part-time or are self-employed.)

- 0
- 1
- 2
- 3

4

- 5 or more (please specify):

3. What is your **age**?

- Less than 18 years
- 18 to 24 years
- 25 to 34 years
- 35 to 44 years
- 45 to 54 years
- 55 to 64 years
- 65 or more years

4. Are you **male or female**?

- Male
- Female

5. Do you have a valid **U.S. driver's license**?

- Yes
- No

6. Which of the following best describes your **ethnicity**?

- Hispanic
- Asian
- African American
- Caucasian/White
- Other (please specify):

7. **How many children** (those under the age of 16 years) usually live in your home?

- 0
- 1
- 2
- 3
- 4 or more (please specify):

8. Which of the following best describes your **household's total annual income** from all sources, before taxes, for all members of your household in 2014? (Income data is very important for developing models that predict vehicle ownership behavior and thus changes in vehicle composition of households over time.)

- Less than $10,000
- $10,000 to $19,999
- $20,000 to $29,999
- $30,000 to $39,999
- $40,000 to $49,999
- $50,000 to $59,999
- $60,000 to $74,999
- $75,000 to $99,999
- $100,000 to $124,999
- $125,000 to $149,999
- $150,000 to $199,999
- $200,000 or more

9. What is the **highest level of education** you have completed?

- I **did not** complete **high school.**

- I completed **high school** (or equivalent).
- I completed **some college**, but **no degree**.
- I obtained an **associate's or technical degree** (or equivalent).
- I obtained a **Bachelor's degree.**
- **I obtained a Master's degree or higher.**

10. Which of the following best describes your **employment status**?

- Employed, working 40 or more hours per week
- Employed, working 20 hours per week
- Student, working part time
- Student, not work
- Not employed, looking for work
- Not employed, not looking for work
- Retired
- Disabled, not able to work

11. What is your **marital status**?

- Single
- Married
- Divorced
- Widowed

12. So that we can link respondent data to neighborhood features (like population density and access to transit services, and use those variables in our mathematical models), please let us know **your home street address**? (Example: "4500 Guadalupe Street") And please feel free to round the number to the block level. (For example, 4553 becomes 4500).

13. What is your **home zip code?**

THANK YOU FOR COMPLETING OUR SURVEY!

We would like to **send you a copy of our report**, if that is of interest to you, and to contact you with any follow-up questions we may have. (This is especially helpful if we need to clarify an answer provided here.) Please allow us to do that by providing your **email address.**

Do you have any **comments or suggestions** for us?

Appendix B. Texas Survey

qualtrics

Start

A Survey of New Travel Technologies

UT Austin Internal Review Board # 2014-09-0078

Dear Respondent,

The Center for Transportation Research at **The University of Texas at Austin** is conducting a research study to explore preferences for and adoption of emerging autonomous and connected vehicle technologies and related traffic management strategies.

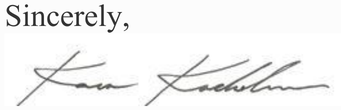
Autonomous vehicles, connected vehicles, and various smartphone applications are new technologies with potential to improve traffic safety and mobility, and reduce emissions. Policymakers and transportation system planners need to assess how quickly such technologies will be adopted in order to develop optimal policies and strategies for traffic operations and management.

- The survey will take approximately **20 minutes** to complete.
- The survey will ask questions about you, your travel patterns, your opinion on speed limit restrictions, your vehicle crash history, and your preferences for various autonomous and connected vehicle technologies.
- Your individual responses are **CONFIDENTIAL**. No names or other identifying information will be used in preparing the data for analysis.
- There are no risks involved in participation in this study and no direct benefits.
- **Your input and opinions** are **VERY IMPORTANT**, since it is critical that a variety of perspectives be present in this survey.

If you have any questions or comments about this study, please feel free to contact me personally at **kkockelm@mail.utexas.edu** or (512) 471-0210. If you have any questions about your rights as a research participant, please contact UT Austin's Office of Research Support by phone at (512) 471-8871 or email at **orsc@uts.cc.utexas.edu**. Your completion of the survey indicates your willingness to participate in the study.

Thank you very much for your time and cooperation.

Sincerely,



Dr. Kara Kockelman
Professor of Transportation Engineering & Faculty Sponsor
www.caee.utexas.edu/prof/kockelman

Section 1 – Autonomous Vehicles

Please TAKE YOUR TIME on this survey. There are many novel questions in this survey that require careful reading and thoughtful answers. Those completing the survey in less than 15 minutes are unlikely to have read many questions.

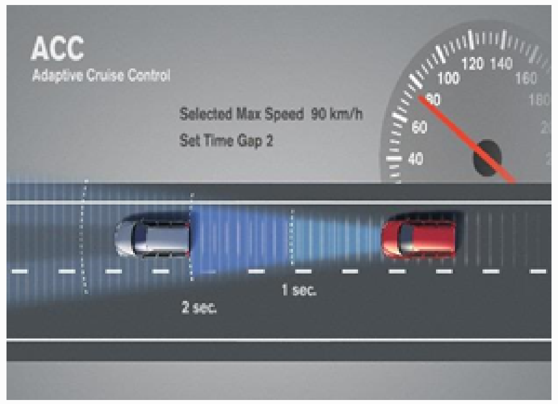
SECTION 1: AUTONOMOUS VEHICLES

Please read carefully before moving forward.
The National Highway Traffic Safety Administration (NHTSA) has defined five technology levels for vehicle automation technology. Levels 0 through 2 encompass technology that is commercially available today; Level 3 and Level 4 are emerging. These levels are defined as follows:

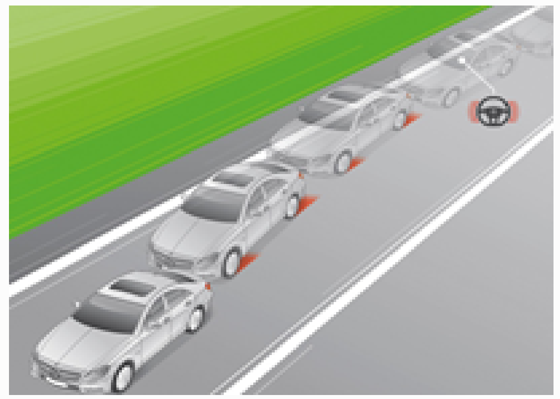
Technologies Currently Available for Consumers:

*No-Automation (**Level 0**).* The driver is completely responsible for the primary vehicle controls: braking, steering, throttle, and motive power.

*Function-specific Automation (**Level 1**).* One or more specific control functions are automated. **Examples** include electronic stability control or pre-charged brakes (the vehicle automatically assists with braking to enable the driver to regain control after skidding or stop faster than possible by acting alone). Other examples include adaptive cruise control (the ability of a vehicle to adjust its speed while in cruise control mode to maintain a safe following distance from a vehicle in front) and lane centering assistance (automatically adjusts the vehicle's steering angle if the driver begins to wander out of the lane).



Adaptive Cruise Control


Lane Centering Assistance

*Combined Function Automation (**Level 2**).* Automation of at least two primary control functions designed to work together to relieve the driver's control of those functions. **Examples** include a combination of adaptive cruise control and lane centering assistance.

Emerging Technologies:

*Limited Self-Driving Automation (**Level 3**).* Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic and environmental conditions. This technology allows the driver to rely heavily on the vehicle to monitor for changes in those conditions, which may require the driver to interfere from time to time. The driver is still expected to be available for occasional control, but after a warning and some comfortable transition time (3 to 5 seconds). For example, the vehicle may be able to drive itself at low speeds or on freeways during good weather, but would need to transition to human control when turning onto higher-speed streets or if inclement weather is encountered.


Level 3 Self-Driving Vehicle

*Full Self-Driving Automation (**Level 4**).* The vehicle is designed to perform all driving functions for the entire trip. This design anticipates that the driver will provide the destination or navigation input, but the driver is not expected to be available for vehicle control at any time during the trip.

Level 4 Self-Driving Vehicle

1. Did you **understand** the description of **automation technology levels**?

- Yes
- No

2. Have you ever heard of Google's Driverless Cars prior to participating in this survey?

- Yes
- No

3. Select the most advanced level (if any) of **vehicle automation technology** present in the vehicle(s) that you (or your household members) own or lease?

- My household has **no vehicles** right now.
- I have **no automation (Level 0)** on vehicles in my household.
- I have at least one vehicle with **Level 1** automation technology in my household.
- I have at least one vehicle with **Level 2** automation technology in my household.
- I have at least one vehicle with **Level 3** automation technology in my household.

○ I **do not know** if my vehicles have any of these technologies.

4. **How interested** are you in **owning or leasing a completely autonomous (Level 4) vehicle** (assuming it were affordable for your household)?

○ Very interested

○ Moderately interested

○ Slightly interested

○ Not interested

5. Does your household **plan to buy or lease** a vehicle in the **next 5 years**?

○ Yes, we **plan to buy or lease** a vehicle in the next 5 years.

○ No, we **do not plan to buy or lease a vehicle** in the next 5 years.

6. **How much additional money** would you be **willing to pay to** add the following automation technologies to your next vehicle (on top of your conventional Level 1 vehicle price)?

	Additional money you expect to pay
Level 2. Combined Function Automation	▼
Level 3. Limited Self-driving	▼
Level 4. Full Automation	▼

Note: For the **remaining questions of this section**, the term "Autonomous Vehicle" will mean a fully automated (**Level 4**) vehicle.

7. In the following areas, what level of concern do you anticipate experiencing in regards to the following potential issues, after autonomous vehicle technology has been **tested and approved for sale** by the National Highway Transportation Safety Administration (NHTSA)?

	Very Worried	Slightly Worried	Not Worried
Equipment or system failure in adverse conditions (example: during heavy rainfall)	○	○	○
Legal liability for "drivers"/owners	○	○	○
Hacking of the vehicle's computer systems	○	○	○

Privacy, such as disclosure of travel destinations to third parties	○	○	○
Interactions with non-autonomous vehicles and vulnerable road users (such as pedestrians and bicyclists)	○	○	○
My learning to use autonomous vehicle technology	○	○	○
Affordability	○	○	○

8. Autonomous vehicles may bring certain benefits. Please indicate **how significant you think each of the following benefits** will be when autonomous vehicles are in extensive use.

	Very Significant	Moderately Significant	Slightly Significant	Insignificant
Fewer crashes	○	○	○	○
Reduced traffic congestion	○	○	○	○
Lower vehicle emissions	○	○	○	○
Better fuel economy	○	○	○	○

9. **How much money** are you **willing to pay to save 15 minutes** of travel time during a typical **30-minutes-long ONE-WAY journey** you make at least once a week (for example, home to work)?

[▾]

10. Which of the following activities do you do **at least once a week** while driving? (Please check all that apply.)

Note: Your responses are confidential.

- ☐ Listen to music
- ☐ Text or browse on my cell phone
- ☐ Hold a cell phone to talk on it
- ☐ Talk on cell phone with a hands-free device
- ☐ Eat or drink
- ☐ Smoke
- ☐ I do not drive a vehicle.

11. What **tasks do you think you will perform** while riding in an autonomous vehicle? (Please check all that apply.)

- ☐ Text or talk on cell phone
- ☐ Look out the windows of the vehicle

- Talk to others who are in the vehicle with me
- Sleep
- Watch movies or play games
- Work
- Read for pleasure
- Surf the Internet
- Exercise, stretch, yoga, or something similar
- Eat or drink
- Other maintenance activities (e.g., brushing teeth)
- Put on makeup
- I do not ever intend to ride in a completely autonomous vehicle.
- Other (please specify):

12. Assume that your vehicle can be converted into a self-driving vehicle by **your paying money at the beginning of the trip**. **How much money** would you be willing to pay to ride in this **self-driving vehicle** for simply **a one-way** journey? (Please note that you can use this travel time for new activities, such as reading and working, since you will be traveling in a Level 4 self-driving vehicle.)

Note: Please **assume that you were to be the driver**, so you essentially are paying to avoid driving or having anyone else drive.

	My typical **one-way distance**	**Traveling ALONE: Willingness to pay** to ride in self-driving mode for this **one-way trip**	**Traveling WITH FAMILY: Willingness to pay** to ride in self-driving mode for this **one-way trip**	**Traveling WITH FRIENDS: Willingness to pay** to ride in self-driving mode for this **one-way trip**
Work trip				
Shopping Trip				
Trip to the next closest big city (not the one you live in)				

13. Which vehicle type do you **currently use** for most of your automobile trips?

- **Minicompact car** (Example: Smart Fortwo)
- **Subcompact car** (Examples: Ford Fiesta and Kia Rio)
- **Compact car** (Examples: Hyundai Elantra, Honda Civic, Toyota Corolla, and Volkswagen Golf)
- **Mid-size car** (Examples: Toyota Camry, Ford Fusion, and Audi A4)
- **Large car** (Examples: Chevrolet Impala, Lincoln MKZ, Jaguar XF, and Toyota Avalon)
- **Minivan** (Examples: Ford C-Max, Toyota Sienna, and Fiat 500L)
- **Cargo van** (Examples: Chevrolet Express 1500 Cargo and Ford Transit)
- **Passenger van** (Examples: Chevrolet Express 1500 Passenger and Ford E350 Wagon)
- **Small sport utility vehicle** (Examples: Jeep Compass and Honda CR-V)
- **Standard sport utility vehicle** (Examples: Audi Q5, Jeep Cherokee, and Ford Explorer)
- **Small pickup truck** (Examples: Chevrolet Colorado and Toyota Tacoma)

Standard pickup truck (Examples: Ford F-150, Chevrolet Silverado, and Nissan Titan)

14. Bigger vehicles (for example, cargo vans) may allow you to relax while riding in the self-driving mode. **Which one of the following decisions** are you likely to take **when self-driving vehicles become common**?

- I will **sell** my current vehicle and **buy a bigger** one.
- I will **not sell** my current vehicle, but will **rent a bigger** vehicle for **long-distance** trips (50 miles or longer).
- I will **buy a bigger** vehicle.
- I will **not buy a bigger** vehicle, but I will **rent a bigger** vehicle for **long-distance** trips (50 miles or longer).
- I will **not buy or rent** a **bigger vehicle**.
- Other (please, specify):

15. If I am in a Level 4 vehicle, I think I will **let my vehicle drive itself** when I am ____. (Please check all that apply.)

- traveling on any kind of roadway
- traveling on freeways
- traveling on less congested city streets
- traveling on highly congested city streets
- traveling in scenic areas
- parking my vehicle
- in other situations (please specify):

16. At **what stage** of autonomous vehicle design and adoption will you be willing to start using autonomous vehicles? (Assume autonomous vehicles will be affordable for you)?

- As soon as autonomous vehicles are approved for **sale to the public** in the U.S.
- When at least **10%** of the people in my community are using such vehicles regularly.
- When at least **50%** of the people in my community are using such vehicles.
- I am **not sure** I will ever be willing to start using such vehicles, regardless of how many autonomous vehicles are on the roads.
- Other (please, specify):

17. Once autonomous vehicles are running safely and reliably on all roadways, **should a child between the age of 13 and 15**, without a driver's license, be **permitted to travel alone** in a driverless vehicle on trips up to 3 miles from his/her home (assuming that the child cannot change the destination, and that somebody you trust will meet the child there)?

- Yes

No

Other (please specify):

18. Assuming 50% of all new vehicles are self-driving vehicles, **will you support** a policy to **disallow conventional** (Level 1) vehicles in most downtowns and other areas with high pedestrian activity?

Yes

No

Other (please specify):

Section 2 - Crash history, speed limits, and other opinions

SECTION 2: CRASH HISTORY, SPEED LIMITS, AND OTHER OPINIONS

1. **How many years** have you been a licensed driver?

2. How many **moving violations** (example: speeding tickets, but **NOT** parking tickets) have you received in the last 10 years?

3. **Red light cameras** (traffic enforcement cameras that capture images of vehicles entering intersections during red traffic lights) exist in 26 U.S. states. Most studies show that these cameras **reduce injury crashes** by 25% to 30%, though some people argue that red-light cameras are used to provide **revenue** for local authorities. **Do you support the use of red light cameras?**

Strongly support

Somewhat support

Neutral

Somewhat oppose

- Strongly oppose

4. **Automated Speed Enforcement (ASE)** technologies, such as speed detection cameras, are used in 13 U.S. states to automatically issue tickets to speeding drivers. Studies have found that ASE **reduces the likelihood of injurious and fatal crashes** by an average of 17%. **Do you support the use of ASE?**

- Strongly support
- Somewhat support
- Neutral
- Somewhat oppose
- Strongly oppose

5. If your local police department started using ASE technology on a roadway with a **speed limit of 30 miles per hour (mph)**, at **what speed** do you think it will be reasonable to **start automatically ticketing** a driver for speeding?

▾

6. **Speed governors** are devices used to limit the maximum speed in vehicles. Studies indicate that higher speeds lead to more frequent and deadlier crashes. **Do you support installing speed governors in all new vehicles?**

- Strongly support
- Somewhat support
- Neutral
- Somewhat oppose
- Strongly oppose

7. The current **maximum speed limit** in any US state is **85 mph**. If manufacturers were required to install **speed governors** in all new vehicles, **what TOP speed do you think they should be limited to?**

▾

8. How do you percieve your **driving ability** in terms of **safety** relative to other drivers?

- I believe I drive **more safely** than most other drivers.

I believe I am **about average** in driving safely.

I believe I am **less safe** than most other drivers.

9. **Over the past 15 years, how many crashes** in which someone was **killed or sustained serious injury** have you been involved in as a **driver, passenger, bicyclist, or pedestrian**?

10. **Over the past 15 years, how many crashes** in which someone experienced only monetary loss (of at least $200) and no injuries have you been involved in as a **driver, passenger, bicyclist, or pedestrian**?

11. Please provide the **details of five (or less) most severe crashes** which you have been involved in as a driver, passenger, pedestrian, or bicyclist in which someone was **killed or sustained injury.**

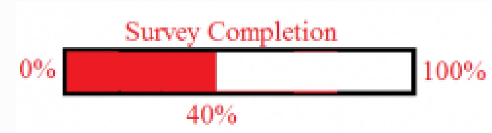
Note: This survey is confidential.

	Your role	**Number of people killed**	**Number of people injured, but not killed**	**Lighting conditions**	**Traffic conditions** at the time of the crash	**Crash location**	**Crash type**	**Primary reason** of crash
Crash 1								
Crash 2								
Crash 3								
Crash 4								
Crash 5								

12. Please provide **details of five (or less) most severe crashes** which you have been involved in as a driver, passenger, pedestrian, or bicyclist in which someone experienced **only monetary loss of more than $200 (and no injuries).**

	Your role	**Total monetary loss of all parties**	**Lighting conditions**	**Traffic conditions** at the time of the crash	**Crash location**	**Crash type**	**Primary reason** of crash
Crash 1							
Crash 2							
Crash 3							
Crash 4							
Crash 5							

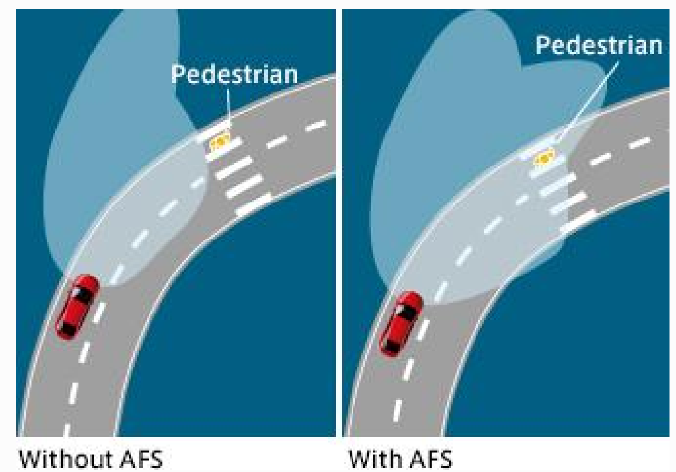
Section 3- Willingness to Pay for Specific Automation Technologies



SECTION 3: WILLINGNESS TO PAY FOR SPECIFIC AUTOMATION TECHNOLOGIES

Note: *This section will ask you about your or your household's willingness to pay for various technologies. Current costs (and future estimated costs) for each technology are provided for illustration purposes.*

1. **Adaptive Headlights:** The vehicle turns the beams according to the driver's steering input so that the vehicle's actual path is always lit up. This system can also point beams up or down when the vehicle crests a hill, according to the position of the vehicle.



Please indicate **your interest** in **adaptive headlights technology?**

- **Very** interested
- **Slightly** interested
- **Not** interested

Do any of your household’s current vehicles presently have **adaptive headlights?**

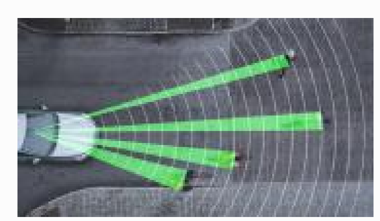
- Yes
- No

Adaptive headlight prices are likely to fall over time, as shown below. **How much** are you **willing to pay** to add this feature to one of your household's current vehicles or to your next vehicle purchase?

Current price	$1,000
Likely price after 5 years	$700
Likely price after 10 years	$500

- Less than $150
- $150 to $249
- $250 to $349
- $350 to $449
- $450 to $549
- $550 to $649
- $650 to $749
- $750 to $849
- $850 to $949
- $950 to $1,049
- $1,050 to $1,249
- $1,250 to $1,500
- I **will not pay anything** to add **adaptive headlights**.

2. **Pedestrian Detection:** This technology detects pedestrians and cyclists on the road and issues a warning to the driver if the vehicle is dangerously close to them.



Please indicate **your interest** in **pedestrian detection technology?**

- **Very** interested
- **Slightly** interested

- **Not** interested

Do any one of your household’s current vehicles have **pedestrian detection**?

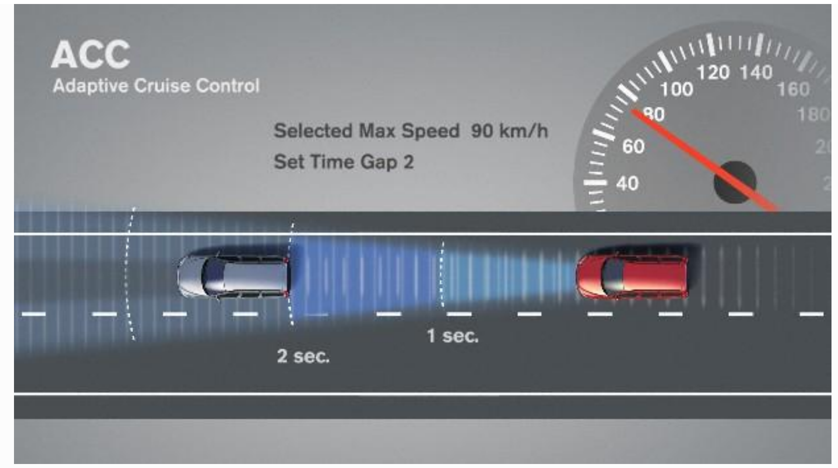
- Yes
- No

Pedestrian detection prices are likely to fall over time, as shown below. **How much** are you **willing to pay** to add this feature to one of your household current vehicles or to your next vehicle purchase?

Current price	$450
Likely price after 5 years	$320
Likely price after 10 years	$230

- Less than $100
- $100 to $199
- $200 to $299
- $300 to $399
- $400 to $499
- $500 to $699
- $700 to $1,000
- I **will not pay anything** to add **pedestrian detection**.

3. **Adaptive Cruise Control:** The ability of a vehicle to adjust its speed to ensure a minimum following distance, so that your vehicle does not hit the car in front of it while driving using cruise control.



Please indicate **your interest** in **adaptive cruise control?**

- **Very** interested
- **Slightly** interested
- **Not** interested

Do any of your household's current vehicles presently have **adaptive cruise control**?

- Yes
- No

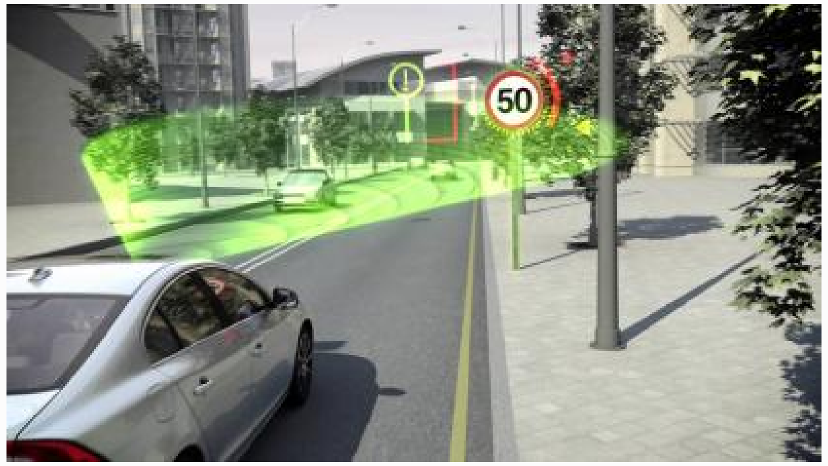
Adaptive cruise control prices are likely to fall over time, as shown below. **How much** are you **willing to pay** to add this feature to one of your household's current vehicles or to your next vehicle purchase?

Current price	\$400
Likely price after 5 years	\$280
Likely price after 10 years	\$200

- Less than \$50
- \$50 to \$149
- \$150 to \$249
- \$250 to \$349
- \$350 to \$449

- $450 to $699
- $700 to $1,000
- I **will not pay anything** to add **adaptive cruise control**.

4. **Traffic Sign Recognition:** This technology will detect road signs and notify the driver about driving restrictions (examples: no passing zone, construction zone, speed limits, and stop signs) on the current stretch of road.



Please indicate **your interest** in **traffic sign recognition technology?**

- **Very** interested
- **Slightly** interested
- **Not** interested

Do any of your household's current vehicles presently have **traffic sign recognition**?

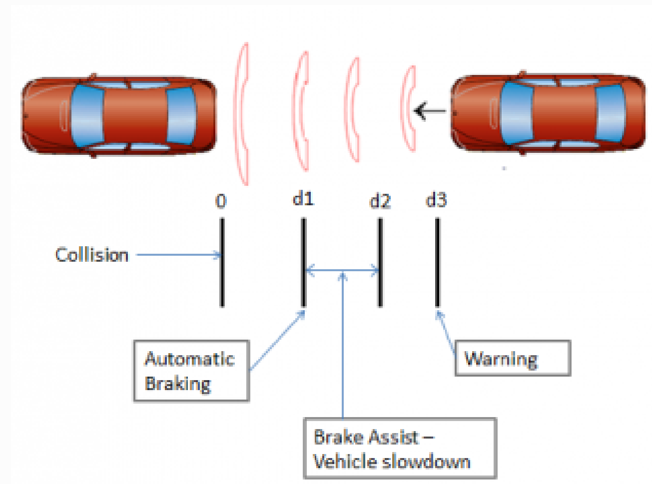
- Yes
- No

Traffic sign recognition prices are likely to fall over time, as shown below. **How much** are you **willing to pay** to add this feature to one of your household's current vehicles or to your next vehicle purchase?

Current price	$450
Likely price after 5 years	$320
Likely price after 10 years	$230

- Less than $100
- $100 to $199
- $200 to $299
- $300 to $399
- $400 to $499
- $500 to $699
- $700 to $1,000
- I **will not pay anything** to add **traffic sign recognition**.

5. **Emergency Automatic Braking:** A vehicle monitors for obstacles on the road. If an obstacle is detected, the vehicle applies its brakes if the driver does not react within a reasonable time frame after the warning.



Please indicate **your interest** in **emergency automatic braking?**

- **Very** interested
- **Slightly** interested
- **Not** interested

Do any of one of your household's current vehicles presently have **emergency automatic braking**?

- Yes
- No

Emergency automatic braking prices are likely to fall over time, as shown below. **How much** are you **willing to pay** to add this feature to one of your household's current vehicles or to your next vehicle purchase?

Current price	$450
Likely price after 5 years	$320
Likely price after 10 years	$230

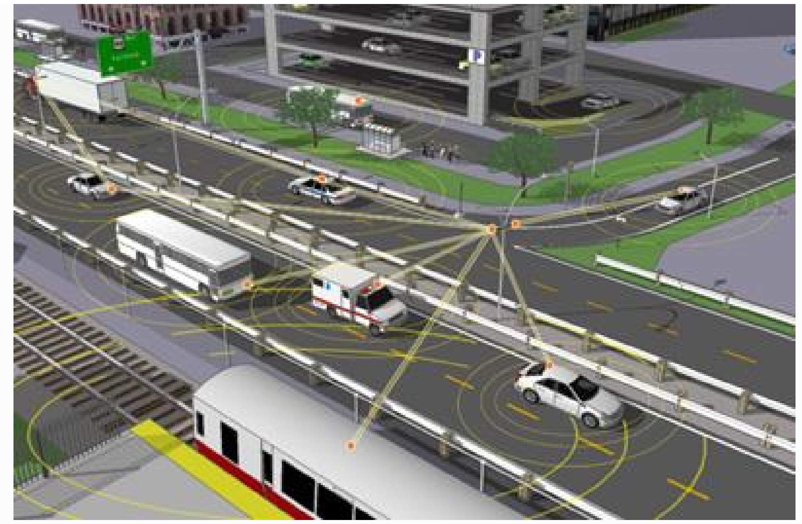
- Less than $100
- $100 to $199
- $200 to $299
- $300 to $399
- $400 to $499
- $500 to $699
- $700 to $1,000
- I **will not pay anything** to add **emergency automatic braking**.

Section 4 – Connected Vehicles

SECTION 4: CONNECTED VEHICLES

Please read carefully before moving forward.
A communications feature may be added to an existing vehicle using a smartphone and some additional equipment with dedicated short range communications (DSRC) technology and inertial sensors. This feature can be used to send alerts to the driver in form of audible sounds (like a message to "slow down" when congestion is forming up ahead or the roadway is deemed slippery) or in text format (like real-time travel times to one's destination). Connectivity is even more valuable when one's vehicle is highly automated, because the vehicle can take corrective actions on its own, without its occupants having to register the alerts (about a coming conflict or speed violation, for example).

The National Highway Traffic Safety Administration (NHTSA) recently announced an advanced notice for proposed rulemaking related to vehicle-to-vehicle communication technology for light-duty vehicles. Connected vehicles are equipped with technology that enables them to **"talk" to nearby vehicles and roadside infrastructure** (like traffic lights' control boxes). This technology can be used for a variety of purposes, such as sharing information about nearby moving objects, roadway conditions, slow vehicles, and better routes. Connected vehicles have the potential to increase roadway safety by reducing the number of crashes caused by human error.



1. **Prior to participating** in this survey, had you ever **heard of connected vehicles**?

- Yes
- No

2. Would you **add connected vehicles technology** to any of your current or future vehicles (assuming it costs under $200 per vehicle)?

- I would **definitely add** connectivity to at least one of my household's current or future vehicles.
- I think I would **add** connectivity to at least one of my household's current or future vehicles.
- I really **do not know** whether I would add connectivity to any of my household's current or future vehicles.
- I **probably** would **not add** connectivity to any of my household's current or future vehicles.
- I **definitely** would **not add** connectivity to any of my household's current or future vehicles.

3. How much are you and/or your household **willing to pay** to **add connectivity to one** of your current vehicles or to one of your future **conventional** (**not self-driving**) vehicles?

- $0 to $99
- $100 to $199
- $200 to $299
- $300 to $399
- $400 to $499
- $500 to $599

- $600 to $799
- $800 to $999
- $1,000 or more
- I do not want to add it.

4. How much are you and/or your household **willing to pay** to **add connectivity to one** of your future **self-driving** (Level 4) vehicles?

Note: A self-driving vehicle that is "connected" can **anticipate and respond** to emerging conflicts, signal timing changes, and other **events it can not see** (with its cameras and LIDAR device). Such information is relayed to it by other connected vehicles and roadside devices that cities and states may invest in.

- $0 to $99
- $100 to $199
- $200 to $299
- $300 to $399
- $400 to $499
- $500 to $599
- $600 to $799
- $800 to $999
- $1,000 or more
- I do not want to add it.

5. Please indicate your **interest** in having the following **connected vehicle technologies** in one of your current vehicles or in your future vehicle:

	I am **already using** this.	I am **interested in using** this.	I am **not interested in using** this.
Real-time traffic information (examples: travel time information based on congestion, traffic-jam-ahead warnings)	○	○	○
Alert about the presence of **speed cameras** on route	○	○	○
Information about **nearby available parking spaces**	○	○	○
Automatic notification to emergency personnel in the event of an accident	○	○	○
Automatic monitoring of driving habits by insurance companies to provide more appropriate (usage-based) rates	○	○	○
Personal restrictions (example: restrict the vehicle from exceeding certain speed limits when a teenager is driving)	○	○	○

Alcohol detection: Automatically prohibit the driver from starting the vehicle if he/she has a blood-alcohol level above a pre-determined threshold	○	○	○
Road sign information (examples: speed limit and stop signs) using a heads-up display	○	○	○
Cabin pre-conditioning (example: pre-warming or pre-cooling the vehicle)	○	○	○
Vehicle health report (examples: maintenance issues and software updates)	○	○	○
Vehicle life-cycle management (example: notification of vehicle service suggestions)	○	○	○

6. Please indicate your **interest** in using the following **technologies while driving your vehicle** (assuming that these activities are **safe and legal** to perform while driving):

	I am **already using** this.	I am **interested in using** this.	I am **not interested in using** this.
Surfing the Internet via a built-in car display	○	○	○
In-vehicle feature allowing one to **compose and read emails**	○	○	○
Operating a smartphone using controls on the steering wheel	○	○	○

7. Assuming that a high percentage (80%) of vehicles **are connected**, please indicate **your opinions** on the following **traffic management strategies.**

	I **support** this strategy.	I **do not support** this strategy.	I **do not have an opinion** about this yet.
Real-time modification of traffic signal timing to ease congestion (example: longer green time if vehicle lines are forming)	○	○	○
Real-time adjustment of parking prices (example: higher prices for busier blocks)	○	○	○
Variable toll rates on congested corridors to keep traffic moving at peak times of the day	○	○	○
Variable speed limits based on road and weather conditions	○	○	○

8. Automobile technologies have many different impacts on the environment and quality of life. Please **rank the important areas** (in decrease order of importance) for improvement in automobile technologies:

	Rank 1 **(most important)**	Rank 2	Rank 3	Rank 4 **(least important)**
Emissions (including air quality, but not greenhouse gas emissions)	○	○	○	○
Safety	○	○	○	○
Travel times (and congestion)	○	○	○	○
Energy use & climate change	○	○	○	○

9. Please provide any **other impacts** (not included in question 8) that you would like to rank, & note its ranking:

	Impact	**Rank**
	Not included in question 8	
Other impact #1		▼
Other impact #2		▼

Section 5 – Other Strategies (carsharing, ridesharing, and tolls)

SECTION 5: CARSHARING, RIDESHARING, AND TOLLS

1. Do you carry/own a **smartphone**?

- Yes
- No

2. Are you **familiar** with **Zipcar, Car2Go,** or other **carsharing** programs?

Note: Uber, Lyft, and other on-demand taxi services are **not carsharing** programs.

- Yes
- No

3. Have you **ever been a member** of **Zipcar** or any other **carsharing programs**?

- Yes
- No

4. Please select **your reason(s) for being a member** of a carsharing program. (Please check all that apply.)

- ☐ Carsharing **saves/saved money**.
- ☐ Carsharing **saves/saved time**.
- ☐ Carsharing is/was a more **environmentally friendly** practice than private vehicle ownership.
- ☐ Carsharing is/was a **necessity** for me because I do/did not own a vehicle.
- ☐ Carsharing is/was a **good back-up option** when my vehicle is/was in a garage for service.
- ☐ Sometimes, I need/needed a **different type** of a vehicle (e.g., a pickup truck) that I do/did not have.
- ☐ Other (please specify):

5. What are the **reasons you have not joined** a carsharing program? (Please check all that apply.)

- ☐ Carsharing programs are **not available in my city**.
- ☐ Shared vehicle availability is **unreliable**.
- ☐ Shared vehicle locations **are not convenient**.
- ☐ I **own a vehicle**.
- ☐ I **rely on public transit, walking, and/or biking**.
- ☐ Carsharing is **expensive**.
- ☐ Shared vehicles **do not have enough capacity**.
- ☐ It is **too stressful** to be responsible to return a vehicle on time.
- ☐ I am not ready to share a vehicle with **people I do not know.**
- ☐ Other (please specify):

6. Are you **familiar with on-demand taxi services like Uber or Lyft**?

- ○ Yes, I am **familiar** with at least one of these companies.
- ○ No, I am **not familiar** with any of these companies.

7. Have you **ever used Uber, or Lyft as a passenger**?

- Yes
- No

8. Why did you use **Uber or Lyft?** (Please check all that apply.)

- To **save money** (rather than paying for a taxi or for parking)
- To **save time**
- To **try it out**
- To **avoid driving** (example: after drinking)
- No need to worry about parking
- When my **personal vehicle was unavailable** (e.g., in a repair shop)
- Promotion (e.g., a free ride)
- Other (please specify):

9. With whom would you feel **comfortable sharing a ride** on local trips during the daytime? Ride-sharing will reduce your travel cost. (Please check all that apply.)

- With a **stranger**
- With **a friend of one of my friends (whom I have not met before)**
- With my **regular friends and family members**
- Only with really **close friends and family members**
- Other (please specify):

Information for question 10: Shared Autonomous Vehicles (SAVs) are an on-demand autonomous taxi systems that combine autonomous vehicles with carsharing membership features. Program members can call on these vehicles using smartphones or other mobile devices, rather than searching for and walking to an available carsharing vehicle.

10. Assuming **it has been several years**, so your household has had an opportunity **to consider releasing one of the vehicles** it may now own or lease, and assuming that a **large fleet of shared autonomous vehicles** is **available** to you and other Texans, **how often would you use them?** (Please, assume that these options are affordable for you and your household.)

- I think I would **rely entirely** on such a fleet, assuming it is readily available when needed.
- I think I would use them **quite regularly (at least once a week)**.
- I think I would use them **reasonably regularly (at least once a month)**.
- I think I would use them **less than once a month**.
- I think I would **not use them at all**.

Information on taxi costs for questions 11, 12, and 13: Taxis in Austin presently cost about $2.50 to $3.50 per mile. UberX and Lyft (companies providing real time on-demand taxi service) currently charge about $1.50 per mile. Car2Go (a company providing carsharing service) charges $0.80 to $1.25 per mile within its operating geographic area and $15 per hour of parking outside of this area.

11. Assuming it **has been several years**, so your household has had **an opportunity to consider releasing one of the vehicles it may now own or lease**, and assuming that **shared autonomous vehicles** then **cost $1 per mile**, how often would you use them?

- I think I would **rely entirely** on such a fleet, assuming it is readily available when needed.
- I think I would use them **quite regularly (at least once a week)**.
- I think I would use them **reasonably regularly (at least once a month)**.
- I think I would use them **less than once a month**.
- I **don't think** I would ever **use** these.

12. Assuming it **has been several years**, so your household has had **an opportunity to consider releasing one of the vehicles it may now own or lease**, and assuming that **shared autonomous vehicles** then **cost $2 per mile**, how often would you use them?

- I think I would **rely entirely** on such a fleet, assuming it is readily available when needed.
- I think I would use them **quite regularly (at least once a week)**.
- I think I would use them **reasonably regularly (at least once a month)**.
- I think I would use them **less than once a month**.
- I **don't think** I would ever **use** these.

13. Assuming it **has been several years**, so your household has had **an opportunity to consider releasing one of the vehicles it may now own or lease**, and assuming that **shared autonomous vehicles** then **cost $3 per mile**, how often would you use them?

- I think I would **rely entirely** on such a fleet, assuming it is readily available when needed.
- I think I would use them **quite regularly (at least once a week)**.
- I think I would use them **reasonably regularly (at least once a month)**.
- I think I would use them **less than once a month**.
- I **don't think** I would ever **use** these.

Information for questions 14 to 17: **Autonomous vehicles may make travel easier** for many people, and some travelers may decide to live further from the city center, their workplaces, and their children's schools. Alternatively, households living in urban locations will be able to access a low-cost (for example, $1.50 per mile) shared fleet of autonomous vehicles. This will allow them to let go of vehicles they presently own, and turn to other transportation options (like walking, biking, and utilizing autonomous buses for some trips).

14. Approximately **how far** do you **currently** live from the **center of the city/town** in which you spend most of your time?

15. **Which one** of the following **decisions** are you likely to make once autonomous and shared autonomous vehicles become available?

- Move **closer** to the city-center
- Move **farther** from the city center
- **Stay** at my current home location

16. **How much closer** would you like to move relative to **your current home location** once autonomous vehicles and shared autonomous vehicles become available?

17. **How much further** would you like to move relative to **your current home location** once autonomous vehicles and shared autonomous vehicles become available?

18. **Would you support** converting some of your city's currently congested non-toll **highway** sections into tolled lanes when congestion is normally present (in order to keep traffic moving at speeds above 50 mph) **if the toll revenues were used to lower local property taxes**?

- I **definitely** would **support** such a policy.
- I **probably** would **support** such a policy.
- I **do not know** whether I can support such a policy.
- I **probably** would **not support** such a policy.
- I **definitely** would **not support** such a policy.

19. **Would you support** converting some of your city's currently congested non-toll **highway** sections into tolled lanes when congestion is normally present (in order to keep traffic moving at speeds above 50 mph) if the **toll revenues were evenly distributed among residents' Toll Tag accounts**?

- I **definitely** would **support** such a policy.
- I **probably** would **support** such a policy.
- I **do not know** whether I can support such a policy.
- I **probably** would **not support** such a policy.
- I **definitely** would **not support** such a policy.

20. The GPS and/or communications systems on board connected vehicles will enable **time-varying tolls** on **all roadways** that experience congestion. If application of such tolls is the **only reasonable way to curb congestion** on those roadways, **will you support such tolls?**

- I **definitely** would **support** such a policy.
- I **probably** would **support** such a policy.
- I **do not know** whether I can support such a policy.
- I **probably** would **not support** such a policy.
- I **definitely** would **not support** such a policy.

21. What if the **revenues** from such congestion-related tolls are **evenly distributed to all travelers' Toll Tag accounts**, to ensure a base level of travel for everyone, and such credits can also be used for transit, car-sharing, and other travel options, not just private car travel. **Will you support the use of such tolls**, in order to ensure that **excessive congestion is avoided** in your region?

- I **definitely** would **support** such a policy.
- I **probably** would **support** such a policy.
- I **do not know** whether I can support such a policy.
- I **probably** would **not support** such a policy.
- I **definitely** would **not support** such a policy.

Section 6 – Travel Characteristics

SECTION 6: TRAVEL CHARACTERISTICS

1. Which of the following is your **primary means of travel** for the following activities? (Please select one for each activity.)

	Walk	Bicycle	Drive Alone	Drive with Others	Public Transport (Including School Buses)	Not applicable
Work trips (either home to workplace or workplace to home)	○	○	○	○	○	○
School trips (to and from your own school or your child(ren)'s school **WHEN SCHOOL IS BACK IN SESSION**)	○	○	○	○	○	○
Shopping trips	○	○	○	○	○	○
Personal business trips (Examples: gym and doctor appointments)	○	○	○	○	○	○
Social/recreational trips (Examples: dining out and visiting friends)	○	○	○	○	○	○
Other trips (Examples: daycare and computer repair)	○	○	○	○	○	○

2. **How many ROUND trips** did you make for the following **purposes** in the **last 7 days?**

	0 trips	1-2 trips	3-4 trips	5-6 trips	7-8 trips	9 or more trips
Work trips (either home to workplace or workplace to home)	○	○	○	○	○	○
School trips (to and from your own school or your child(ren)'s school **WHEN SCHOOL IS BACK IN SESSION**)	○	○	○	○	○	○
Shopping trips	○	○	○	○	○	○
Personal business trips (Examples: gym and doctor appointments)	○	○	○	○	○	○
Social/recreational trips (Examples: dining out and visiting friends)	○	○	○	○	○	○
Other trips (Examples: daycare and computer repair)	○	○	○	○	○	○

3. What is the **one-way** distance **from your home** to the following locations?

	Less than 1 mile	1-3 miles	3-5 miles	5-10 miles	10-15 miles	More than 15 miles
Grocery store (one you visit the most)	○	○	○	○	○	○
Public transport stop/station	○	○	○	○	○	○
The airport	○	○	○	○	○	○
City's downtown	○	○	○	○	○	○

4. If my vehicle could be set to either self-driving or manual driving when making each trip, I think I would **set it to SELF-DRIVING when** I am making ___ (please check all that apply).

a personal business trip

- all types of trips
- a work trip
- a school trip
- a shopping trip
- (Examples: gym and doctor appointments)
- a social or a recreational trip
- other type of a trip (please, specify):
- I would not use self-driving vehicle.

5. **How many miles** do you estimate you **traveled in a car or truck over the last year**? (This may be your own vehicle, plus miles in a rental car, and miles in anyone else's passenger vehicle over the past 365 days.)

- less than 3,000 miles
- 3,000 to 5,999 miles
- 6,000 to 8,999 miles
- 9,000 to 11,999 miles
- 12,000 to 14,999 miles
- 15,000 to 17,999 miles
- 18,000 to 20,999 miles
- 21,000 or more miles

6. Do you have, or have you ever had, **any disability** that prevents you from manually driving a vehicle? (Please check all that apply.)

- No disability
- Vision impairment
- Mobility issues
- Cognitive disorder
- Other (please specify):

Section 7 – Demographics

SECTION 7: DEMOGRAPHICS

1. Including yourself, **how many people** live in your **household**? (Please do not include anyone who usually lives somewhere else or is just visiting, such as a college student away at school; do not include your roommates if you do not

support each other financially.)

- 1
- 2
- 3
- 4
- 5 or more (please specify):

2. Including yourself, **how many workers** usually live in your **household**? (Please include all the persons in your household who get paid for working full-time, part-time, or are self-employed.)

- 0
- 1
- 2
- 3
- 4
- 5 or more (please specify):

3. What is your **age**?

- Less than 18 years
- 18 to 24 years
- 25 to 34 years
- 35 to 44 years
- 45 to 54 years
- 55 to 64 years
- 65 or more years

4. Are you **male or female**?

- Male

- Female

5. Do you have a valid **U.S. driver's license**?

- Yes
- No

6. Which of the following best describes your **ethnicity**?

- Hispanic/Latino/Mexican American
- Asian/Asian American
- Black/African American
- American Indian/Native American
- White/European White/Caucasian
- Mixed/Multiracial
- Other (please specify):

7. **How many children** (those under the age of 16 years) usually live in your home?

- 0
- 1
- 2
- 3
- 4 or more (please specify):

8. Which of the following best describes your **household's total annual income** from all sources, before taxes, for all members of your household in 2014? (Income data is **very important** for developing models that predict vehicle ownership behavior and thus changes in vehicle composition of households over time.)

- Less than $10,000
- $10,000 to $19,999

- $20,000 to $29,999
- $30,000 to $39,999
- $40,000 to $49,999
- $50,000 to $59,999
- $60,000 to $74,999
- $75,000 to $99,999
- $100,000 to $124,999
- $125,000 to $149,999
- $150,000 to $199,999
- $200,000 or more

9. What is the **highest level of education** you have completed?

- I **did not** complete **high school.**
- I completed **high school** (or equivalent).
- I completed **some college**, but **no degree**.
- I obtained an **associate's or technical degree** (or equivalent).
- I obtained a **Bachelor's degree.**
- **I obtained a Master's degree or higher.**

10. Which of the following best describes your **employment status**?

- Employed, working 40 or more hours per week (including self-employed)
- Employed, working 1-39 hours per week
- Student, working part time
- Student, not work
- Not employed, looking for work
- Not employed, not looking for work
- Retired
- Disabled, not able to work

11. What is your **marital status**?

- Single
- Married
- Divorced
- Widowed

12. So that we can link respondent data to neighborhood features (like population density and access to transit services, and use those variables in our mathematical models), please let us know **your home street address**? (Example: "4500 Guadalupe Street") And please feel free to round the number to the block level. (For example, 4553 becomes 4500.)

13. What is your **home zip code?**

THANK YOU FOR COMPLETING OUR SURVEY!

We would like to **send you a copy of our report**, if that is of interest to you, and to contact you with any follow-up questions we may have. (This is especially helpful if we need to clarify an answer provided here.) Please allow us to do that by providing your **email address.**

Do you have any **comments or suggestions** for us?