THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

0-6849-P1

BEST PRACTICES GUIDEBOOK FOR PREPARING TEXAS FOR CONNECTED AND AUTOMATED VEHICLES

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TxDOT Project 0-6849: Implications of Automated Vehicles on Safety, Design and Operation of the Texas Highway System

JUNE 2016; PUBLISHED OCTOBER 2016

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

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Executive Summary

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 document, *Best Practices Guidebook for Preparing Texas for Connected and Automated Vehicles*, presents the main points of CTR's research on CAVs and develops practice recommendations, emphasizing safety, to assist TxDOT in optimally planning for these new technologies using a holistic and qualitative approach.[1]

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 is assessed here to provide recommendations for TxDOT to pursue in the short term (next 5 years), medium term (five to fifteen years), and long term (15+ years). 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.

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[1] The results are primarily from this project 0-6849: *Implications of Automated Vehicles on Safety, Design and Operation of the Texas Highway System*, but also include some items developed in 0-6838: *Bringing Smart Transportation to Texans: Ensuring the Benefits of a Connected and Autonomous Transport System in Texas,* and 0-6847: *An Assessment of Autonomous Vehicles: Traffic Impacts and Infrastructure Needs.*

Introduction

Smart driving technologies (connected and automated vehicle [CAV] technologies) have drawn significant attention in recent years, due to their rapid development and potential safety, mobility, and environmental benefits (Litman, 2015). In 2010, National Highway Traffic Safety Administration (NHTSA) estimates put the cost of U.S. vehicle crashes at $900 per American per year for purely economic losses, and almost $3,000 when quality-of-life valuations are reflected (Bigelow, 2014). Such annual losses are substantial, and are expected to be dramatically reduced by advances in vehicle automation and communication. This guidebook is the product of work that has begun to quantify in detail the crash-related gains of various vehicle automation and connectivity features; anticipate Texans' adoption rates of such technologies for both personal and commercial uses; and simulate crash contexts under various technologies, network design, and traffic control regimes. Advances in a variety of technologies over the last two decades have been applied to the domain of automobiles specifically, and to intelligent traffic systems (ITS) generally. Two areas of particular interest are automation and connectivity. Automation technologies concern the automation of vehicle control functions (such as steering, throttle, and braking) without human inputs. Connectivity technologies are those that enable vehicles to communicate with each other, the infrastructure, or any other properly equipped device.

The success of CAV technologies will rely on efforts of a number of public and private stakeholders, and as such, a thorough understanding of the potential impacts of these technologies requires a multi-disciplinary approach. This guidebook is a desktop guide for Texas Department of Transportation (TxDOT) staff to assist them in understanding CAV technologies and the current trends in development and deployment. The overview should aid in anticipating the evolution of the Texas fleet and its use under various market (price, technology, demographics, and land use) scenarios; and provide implementation recommendations, to mitigate safety and other impacts, over the short, medium, and long term. Where possible, the guidebook identifies potential best practices for TxDOT and other agencies to cost-effectively facilitate Texans' adoption and use of the top safety and mobility technologies.

The guidebook is divided into five sections:

1) Overview of CAV Technologies
2) The Current Texas Legal Landscape for CAVs
3) Potential Benefits Using CAV Technologies
4) Potential Safety Strategies for TxDOT to Adopt to Prepare Texas for CAV Use
5) Best-Practice Recommendations for TxDOT in Deployment of CAVs in Texas

Section 1. Overview of CAV Technologies

NHTSA's Taxonomy

In 2013, NHTSA released a "Preliminary Statement of Policy Concerning Automated Vehicles." NHTSA regularly provides definitions of different levels of automation, current automated research programs at the U.S. Department of Transportation (USDOT), and principle recommendations 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 least some aspects of a safety-critical control function (e.g., steering, throttle, or braking)" that can occur without direct driver input. Vehicles that can provide safety warnings to their operators, but cannot control functions, are not 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 (L0 to L4), the allocation of vehicle control 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, as described in Table 1.

Table 1: Comparison of 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, & 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.	Adaptive cruise control; automatic braking (dynamic brake support and crash imminent braking); lane-keeping; electric stability control.
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.***	Adaptive cruise control 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.

Key: L0 to L4= Level 0 to Level 4 automation; Vehicle controls=brake, steering, throttle, and motive power

Identifying CAV Technologies

To clarify the scope of CAV technologies, this guidebook uses NHTSA's four-level automation taxonomy, although the research team reviewed the Society of Automotive Engineers' categorizations as well. A wide range of CAV technologies were examined in depth, including their current applications and use, their maturity and fitness for widespread deployment, and their barriers and expected trends for use in coming years. The top five CAV technologies, anticipated to provide the most benefits over the next 10 years, are as follows:

Top 5 CAV Technologies in 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 (ADAS), such as blind spot warning, lane departure warning and lane keeping, forward collision warning, and automated emergency braking.
4. Adaptive cruise control
5. Dynamic route guidance and data sharing

The specific barriers to implementation of these technologies varied by the technology cluster. Cybersecurity, reliability, and infrastructure preparedness were seen as most significant for 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.

Table 2 provides a matrix of current CAV technologies, their automation level, an appraisal of their technological maturity, and the role that TxDOT may play as these evolve into the market. This table is adapted from TxDOT Project 6838[2], a related research project helmed by CTR. Technology maturity was assessed by examining current literature about the development of these smart vehicle technologies. Technologies assigned a ‘high’ maturity have already been included in recent car models, while technologies assigned ‘low maturity’ have seen little to no testing or use in real-time driving conditions. Those assigned a ‘medium’ maturity have seen some testing in car models, but are expected to be improved considerably as time progresses. TxDOT’s role in advancing the market for CAV technologies is divided into three flexible categories: infrastructure, policy, or a combination of both. The ‘infrastructure’ label suggests that TxDOT can help promote adoption or development of the technology by improving roadway conditions and other operational aspects. Conversely, the ‘policy’ category was used to identify technologies that might not deserve immediate infrastructure modifications for safe operation, but whose development would benefit from TxDOT either forming or promoting policy that helps regulate the testing and sale of these technologies.

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[2] Detailed documentation for Project 0-6838 will be available in the final project report, with publication likely in 2016. Project details and deliverables are provided in the CTR Library Catalog: http://ctr.utexas.edu/library/.

Table 2: List of CAV Technologies Benefits, Maturity, and the Role of TxDOT

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

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

Section 2. The Current Texas Legal Landscape for CAVs

Pertinent laws and legal requirements governing auto safety and transportation were passed decades before development of CAVs.

Numerous public benefits are associated with CAVs, but these technologies also present risks and challenges for our transportation system.[3] Nearly all of the pertinent laws and legal requirements governing auto safety and transportation were passed decades before the development of CAVs. There is uneasiness about the safety and privacy risks that CAVs pose to the public. These concerns stem from existing laws that do not address CAV technologies directly, which could have an unintended effect on the future of CAVs. Some laws may unwittingly impede the deployment of CAVs by imposing unnecessary constraints, while other laws may do too little to address new risks arising from potential invasions of privacy, security, and even the management of safety hazards unique to CAVs.

NHTSA cautions against a state legal regime that adopts a legal, yet unregulated approach to CAV testing and deployment.

This bird's eye view of the intersection of the law and the use of CAVs in Texas reveals several areas that deserve legislative and regulatory attention (as well as additional research) in the near term. Most immediate is the need for policymakers to consider whether the testing and deployment of CAVs in the state will benefit from more formal legal oversight. The existing laws in Texas do not seem to contemplate the emergence of driverless or passively operated cars, and yet, as currently drafted, the deployment of vehicles without drivers (albeit with one "operator" somewhere in the vehicle) appears to be legal. Presumably, then, any person with a valid driver's license could retrofit and operate a driverless vehicle legally on Texas public roadways, without additional regulatory oversight, restrictions, or other operational requirements.

Existing laws in Texas do not seem to contemplate driverless or passively operated cars. Yet, as currently drafted, the deployment of vehicles without drivers (albeit with one "operator" somewhere in the vehicle) appears to be legal.

A second near-term issue at the intersection of CAVs and Texas law that emerges is the need for some adjustments to current liability rules to provide greater predictability—particularly to TxDOT—as CAVs are tested and deployed on Texas roadways. Such anticipatory legislative direction could lay some essential groundwork: a clarification of what constitutes "notice" of a malfunction in traffic devices in the wake of electronic signals; clarifications of what constitutes road hazards that need to be reasonably addressed with respect to CAVs; and direction for several other discrete liability-related issues. While there are certain topics—e.g., design standards governing privacy and safety of CAVs—that benefit from national attention, there are other topics that are not only in need of state legislative guidance, but for which the lack of legal action itself constitutes a choice. Under Texas law,

State legislation that anticipates and addresses the complexity of CAV crash litigation will be beneficial.

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[3] This section is adapted from the previously described TxDOT Project 0-6838.

CAVs appear to be legal on state highways without special notice, insurance, certifications, testing, or reporting. Under current law, Texas agencies are also likely to face increased liabilities with respect to these vehicles and increased pressure to manage and share personal data on registered owners and/or drivers of these vehicles. State agencies will also find themselves under increased pressure for the special CAV use of roadways. Without legislation addressing these issues, state agencies and some local governments may find themselves not only without legislative guidance, but in some cases blocked or constrained by existing laws in their ability to resolve conflicts in ways that appear consistent with the larger public interest. Charting out a number of additional legislative initiatives should facilitate the smooth integration of CAVs onto Texas highways, both by providing predictability to the CAV industry and increasing the public's trust in the safety of the vehicles. Table 3 provides an overview of this larger set of recommendations, with the shaded cells highlighting those items that are likely to be of greatest interest to TxDOT. The italicized cells point to those issues that do not yet appear ready for legal action, but nevertheless warrant attention.

Under current law, Texas agencies are likely to face increased liabilities with respect to these vehicles and increased pressure to manage and share personal data on registered owners and/or drivers of these vehicles.

Table 3: Major Legislative/Policy Recommendations

Safety on the Highway	Legality Section	Liability	State Responsibilities/ Liability	Privacy and Security	Advance Broader Public Goals in CAV Innovation
Testing and development	**Clarify the identity of 'Operator'**	Streamline simple crash claims	**Clarify what constitutes 'notice' for malfunction in digital traffic**	Improve consumer information	*Collect reports/information on CAV*
Vehicle registration/ certification	**Clarify whether operator needs to be on board**	Address other difficult liability issues	**Exempt license plates and other identifiable information from disclosure under the State Open Records Act**	Restrict the sharing or sale of consumer information in CAVs to third parties	*Encourage greater innovation on wide-ranging public benefit*
Added operator requirements	**Adjustments for truck platoons**		Require state agencies to alert individuals when their privacy is breached	Criminalize hacking	
License plate tags or other markers	*Legalize texting and other bad behavior*			*Encourage innovation in cyber security*	
Rules for intensive uses (e.g., truck platoons)					

Section 3. Potential Benefits of Using CAV Technologies

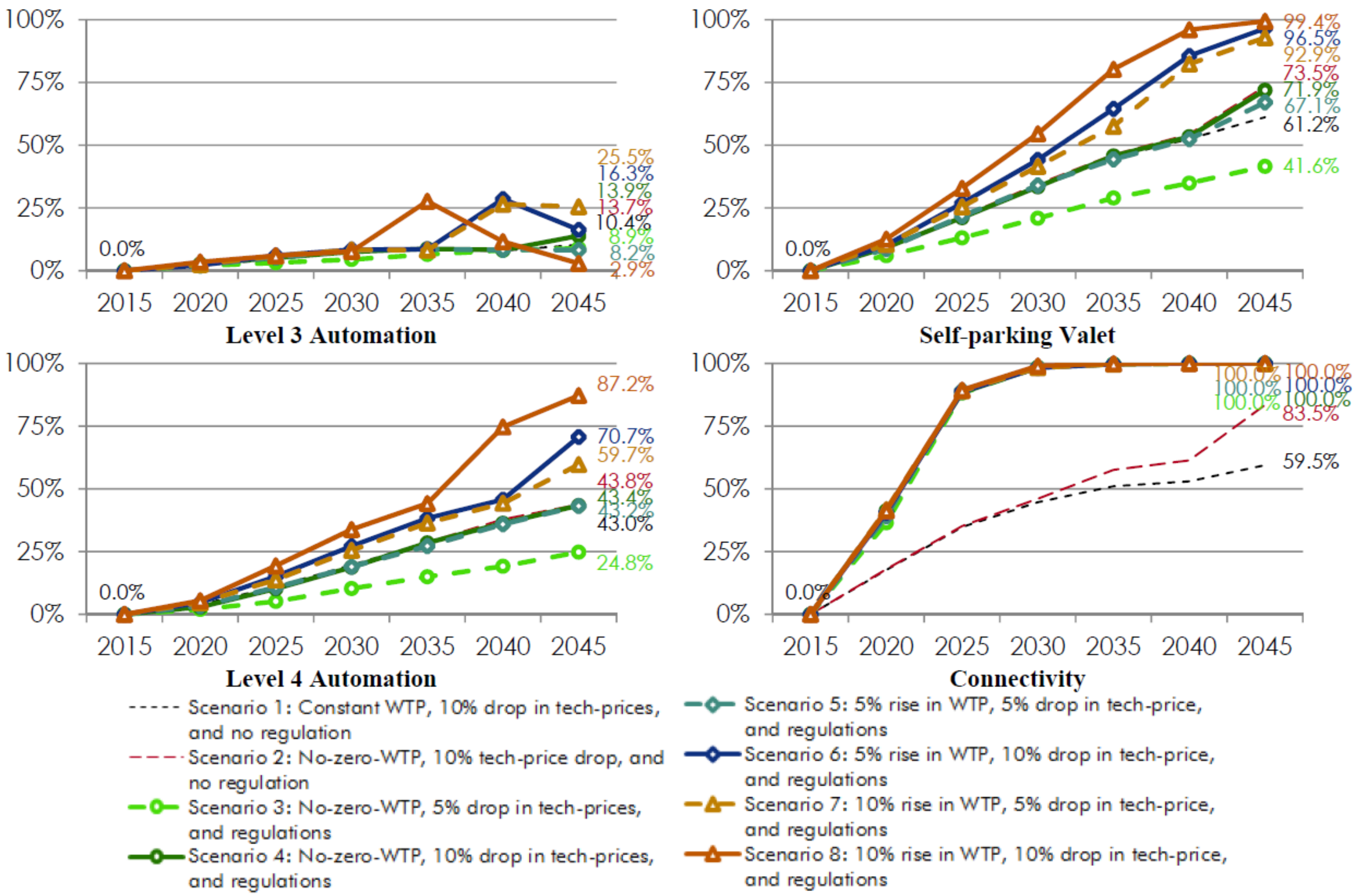
In this section, a snapshot of research results develops context for recommendations presented later in this guidebook.

Assessing National and Texas Opinions on CAV Technologies

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, 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.

A second, Texas-based survey, which examined a variety of perception and attitude analyses using various econometric models, was also developed (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 results of the national survey's fleet evolution simulation indicate that around 98% of the U.S. vehicle fleet is likely to have ESC and connectivity in years 2025 and 2030, respectively. The NHTSA current and probable 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 were estimated to have adoption rates of more than 90% in 2045. 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 (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. The simulation framework results for self-parking valet, Levels 3 and 4 automation, and connectivity for various scenarios are shown in Figure 1.


Level 3 Automation

Self-parking Valet

Level 4 Automation

Connectivity

Figure 1: Estimated Automation Adoption Rates for US Light-duty Vehicles (Bansal & Kockelman, 2015)

The opinion-related summaries of the U.S.-wide survey indicate that around 88.2% of Americans believe that they are great drivers and around three-quarters enjoy driving a car. 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%), followed by luxury vehicle manufacturers (49%), appear to be the top choices of Americans for developing Level 4 AVs. This survey question was based on the presumption that respondents could hypothetically select who actually develops the Level 4 AVs. It is obvious that consumers will not choose who develops Level 4 technology, but it provides a snapshot of customer's trust in specific types of companies. Roughly the same shares of respondents reported WTP of $0 to use AVs for either short-distance (42%) or long-distance (40%) trips. The average number of long-distance trips (over 50 miles) was estimated to increase by 1.3 miles (per person per month) due to the adoption of AVs.

The results of the Texas survey suggest that around 41% of Texans are not ready to use SAVs 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. Talking to other passengers and looking out the window would be 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 decrease crashes: 54% and 53% of the respondents, respectively, indicated that these benefits will be very significant.

The Texas survey suggests that around 41% of Texans are not yet ready to use SAVs.

Those who support speed regulation and have higher household income are estimated to pay more for all levels of automation and connectivity.

The Texas-wide survey data was used in ordered probit and interval regression models to estimate and 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

Older and more experienced licensed drivers are expected to place lower value on these technologies.

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, which is Uber's economy ride-sharing option, 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.

Estimated Safety Benefits of CAV Technologies

CAV technologies are expected to reap considerable safety benefits by reducing crash rates and lessening the severity of injuries resulting from crashes. Li & Kockelman (2016) estimated the safety benefits from use of several CAV technologies by using crash data from the National Automotive Sampling System's (NASS) 2013 General Estimates System (GES) database. The reported crashes are organized into 37 pre-crash scenarios, which refer to a specific event that occurred immediately before the crash. Table 4 lists these pre-crash scenarios along with the corresponding crash type that typically results from each scenario.

Table 4: 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	

No.	Pre-Crash Scenario	Crash Type
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

The economic cost of crashes refers to the monetary loss of life, goods, and services due to vehicular crashes. Economic costs incorporate estimates of the benefits of goods lost due to a crash and the productivity lost due to an injury or fatality. Some of the costs that may be included in economic costs are medical costs, legal fees, emergency service bills, travel delay, and property damage. We estimated the economic unit costs of reported and unreported crashes at different levels of severity ranging from crashes involving property damage only to crashes resulting in a fatality. The Maximum Abbreviated Injury Scale (MAIS) is a common system for categorizing the severity of a crash. Table 5 shows each MAIS crash level along with its estimated economic cost.

Table 5: Economic Costs of Crashes by MAIS Severity Level

MAIS Severity Level	Economic Cost (2012 U.S. Dollars)
Fatality (MAIS6)	$1,496,840
Critical Injury (MAIS5)	$1,071,165
Severe Injury (MAIS4)	$422,231
Serious Injury (MAIS3)	$194,662
Moderate Injury (MAIS2)	$59,643
Minor Injury (MAIS1)	$19,057
No Injury (MAIS0)	$3,042

To estimate the potential economic savings of various CAV technologies, several of them were mapped to specific pre-crash scenarios (Table 6).

Table 6: Mapping Pre-Crash Scenarios to CAV Technologies based on 2013 GES

No.	Pre-Crash Scenario	Mapping Safety Applications
1	Vehicle failure	Control Loss Warning (CLW)
2	Control loss with prior vehicle action	
3	Control loss without prior vehicle action	
4	Running red light	Cooperative Intersection Collision Avoidance System (CICAS)
5	Running stop sign	
6	Road edge departure with prior vehicle maneuver	Road Departure Crash Warning (RDCW) + Lane Keep Assist (LKA)
7	Road edge departure without prior vehicle maneuver	
8	Road edge departure while backing up	
9	Animal crash with prior vehicle maneuver	Automated Emergency Brakes (AEB) + Electronic Stability Control (ESC)
10	Animal crash without prior vehicle maneuver	
11	Pedestrian crash with prior vehicle maneuver	V2Pedestrian
12	Pedestrian crash without prior vehicle maneuver	
13	Pedalcyclist crash with prior vehicle maneuver	V2Pedalcyclist
14	Pedalcyclist crash without prior vehicle maneuver	
15	Backing up into another vehicle	Backup Collision Intervention (BCI)
16	Vehicle(s) turning - same direction	Blind Spot Warning (BSW) + Lane Change Warning (LCW)
17	Vehicle(s) changing lanes - same direction	
18	Vehicle(s) drifting - same direction	
19	Vehicle(s) parking - same direction	Self Parking Valet System (SPVS)

No.	Pre-Crash Scenario	Mapping Safety Applications
20	Vehicle(s) making a maneuver - opposite direction	Do Not Pass Warning (DNPW)
21	Vehicle(s) not making a maneuver - opposite direction	
22	Following vehicle making a maneuver	Forward Collision Warning (FCW) + Cooperative Adaptive Cruise Control (CACC)
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	CICAS
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	Automatic Emergency Braking (AEB) + ESC
33	Evasive action without prior vehicle maneuver	
34	Non-collision incident	None
35	Object crash with prior vehicle maneuver	AEB + ESC
36	Object crash without prior vehicle maneuver	
37	Other	Combined Impacts of Safety Applications

Conservative, moderate, and aggressive effectiveness assumptions were made based on engineering judgement due to current uncertainty in estimating crash reduction rates due to CAV technologies. Table 7 shows the economic costs and functional-years saved using CAV technologies under a moderate effectiveness scenario. Functional-years lost is a measure that gauges the time lost as a result of motor vehicle crashes, which includes time lost due to fatalities and productivity lost to injury.

Table 7: Annual Economic Cost and Functional-Years Savings Estimates from Safety Benefits of CAV Technologies under Moderate Effectiveness Scenario (Per Year, based on 2013 GES Crash Records)

No.	Combination of Safety Applications	Pre-Crash Scenario	Economic Costs Saved ($1M in 2013USD)	Saved Functional-Years (Years)
1	FCW+CACC	Following vehicle making a maneuver	$54,890	533,500
		Lead vehicle accelerating		
		Lead vehicle moving at lower constant speed		
		Lead vehicle decelerating		
		Lead vehicle stopped		
2	CICAS	Running red light	$25,206	275,600
		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		
3	CLW	Vehicle failure	$16,300	250,900
		Control loss with prior vehicle action		
		Control loss without prior vehicle action		
4	RDCW+LKA	Road edge departure with prior vehicle maneuver	$9,468	157,800
		Road edge departure without prior vehicle maneuver		
		Road edge departure while backing up		
5	SPVS	Vehicle(s) parking - same direction	$6,649	51,800
6	BSW+LCW	Vehicle(s) turning - same direction	$6,407	64,000
		Vehicle(s) changing lanes - same direction		
		Vehicle(s) drifting - same direction		
7	DNPW	Vehicle(s) making a maneuver - opposite direction	$5,042	94,900
		Vehicle(s) not making a maneuver - opposite direction		

No.	Combination of Safety Applications	Pre-Crash Scenario	Economic Costs Saved ($1M in 2013USD)	Saved Functional-Years (Years)
8	AEB+ESC	Animal crash with prior vehicle maneuver	$4,836	59,500
		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		
9	V2Pedestrian	Pedestrian rash with prior vehicle maneuver	$3,649	78,700
		Pedestrian crash without prior vehicle maneuver		
10	BCI	Backing up into another vehicle	$2,792	32,300
11	V2Pedalcyclist	Pedalcyclist crash with prior vehicle maneuver	$2,289	21,000
		Pedalcyclist crash without prior vehicle maneuver		
12	Combined Impacts of Safety Applications	Other	$2,170	32,200
	Totals		***$139,694***	***1,652,200***

In order to understand the ramifications of introducing AVs into the traffic system, the project created a micro-simulation 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. The project employed the modeling software Vissim by the PTV Group, which is a flexible modeling environment that enabled the project to implement an AV driver module through the software's External Driver Module. The research 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 human-operated vehicles (HVs). Various scenarios were designed to analyze the safety of AVs under different conditions, including variations in traffic, volume, and number of lanes. Three intersections in Austin were analyzed to provide a snapshot of the potential intersection behavior of CAVs.

1. The intersection of I-35 and Wells Branch Parkway in Austin was used to represent 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.
2. The intersection at I-35 and 4th street in Austin served as an example of an intersection where the traffic volume is moderate. This network has four one-way double-lane roads that intersect at two stop signs.
3. The intersection at Manor Road and E M Franklin Avenue in Austin represented an intersection with low traffic volume. This network has three one-way double-lane roads that intersect at two stop signs.

Figure 2 shows the results of the simulations ran for I-35 and Wells Branch Parkway. The number of conflicts comprehensively decreased with the addition of AVs in the traffic, from 100% HVs to 100% AVs.

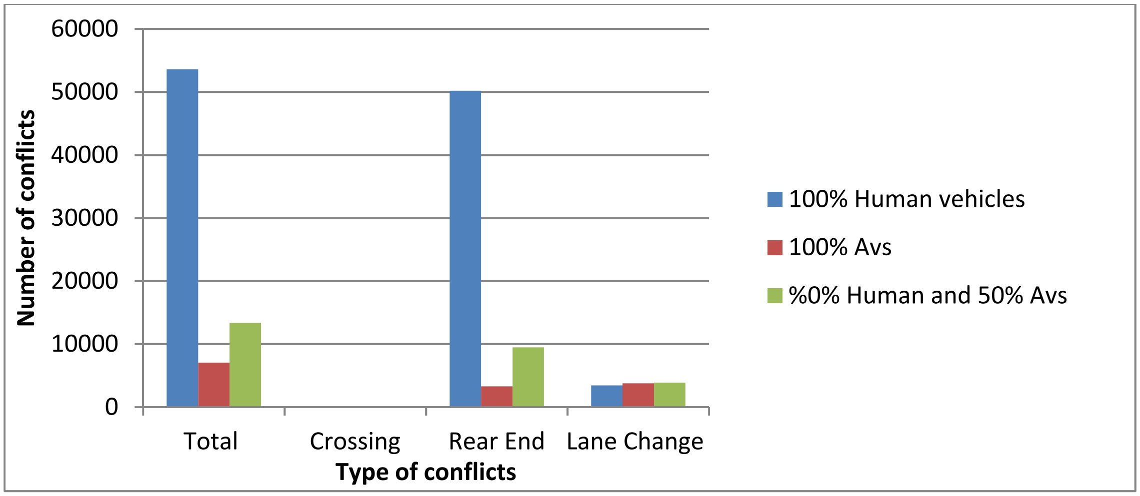


Figure 2: Intersection Conflicts Disaggregated by Type at I-35 and Wells Branch Parkway, Austin, TX

Potential Operational Benefits of CAV Use

CAVs will have operational impacts on the Texas roadway system. With technologies such as CACC using DSRC communication, future CAVs are expected to be able to travel along roadways with smaller headways, as driverless vehicles should react to driving conditions faster than a human driver typically would. To understand the effects of introducing CAVs into today's traffic system, Patel et al. (2016) used a link-based mesoscopic (or mid-scale) dynamic traffic assignment (DTA) model to find the effects of CAVs on congestion and travel times. The researchers also analyzed the effects of rising CAV ownership on transit ridership, CAV repositioning trips, and total personal-vehicle demand using static traffic assignment (STA) simulations. Finally, the team analyzed how connected SAVs may perform relative to privately held CAVs, and how preemptive vehicle relocation and dynamic ride-sharing options affect performance of the downtown transportation network simulated here, over a 2-hour morning-peak period, where most of the trip-making is inbound.

For monitoring CAV effects on congestion, several small test networks from among the top 100 most congested locations and corridors in Texas were assessed (as part of TxDOT Project 0-6847, a related project helmed by this research team). These segments were chosen so that the results would be widely applicable. The mesoscopic simulation used DTA, specifically the cell transmission model, to obtain metrics on total system travel time and time traveled per vehicle, at different proportions of CAVs and HVs on these networks. Along with monitoring the effects of CAVs on traffic, the research team observed the effects of the first-come first-served (FCFS) and tile-based reservation (TBR) intersection-use methods on a test network consisting of 100% CAVs. FCFS (similar to the first-in first-out control) and TBR are assumed to replace all traffic lights in the test networks when only CAVs are on the roads (i.e., no HVs). Figure 3 shows results for the analysis of freeway network travel time for I-35 in Austin. Overall, greater capacity from CAVs' reduced reaction times improved travel times in all freeway networks tested, with better improvements at higher demands.

With these simulations and metrics, different levels of demand and different proportions of CAVs on a variety of test networks were analyzed. Increasing the proportion of CAVs always reduced vehicle travel, as we assumed that CAVs' faster reaction times (versus human drivers) reduce their car-following headways, thus increasing lane capacities and signal-phase capacities naturally. While reduced headways are a reasonable expectation for *advanced stages* of CAV adoption, in the early stages, due to either cultural norms or caution on behalf of manufacturers, there may be no reduction in headway due to CAVs. If so, the capacity increases described here may not materialize. FCFS reservations often perform worse than traditional signals for some networks. At high levels of demand, reservations do not allocate capacity as efficiently as signals or provide progression across upstream and downstream signals, resulting in queue spillback along arterials.

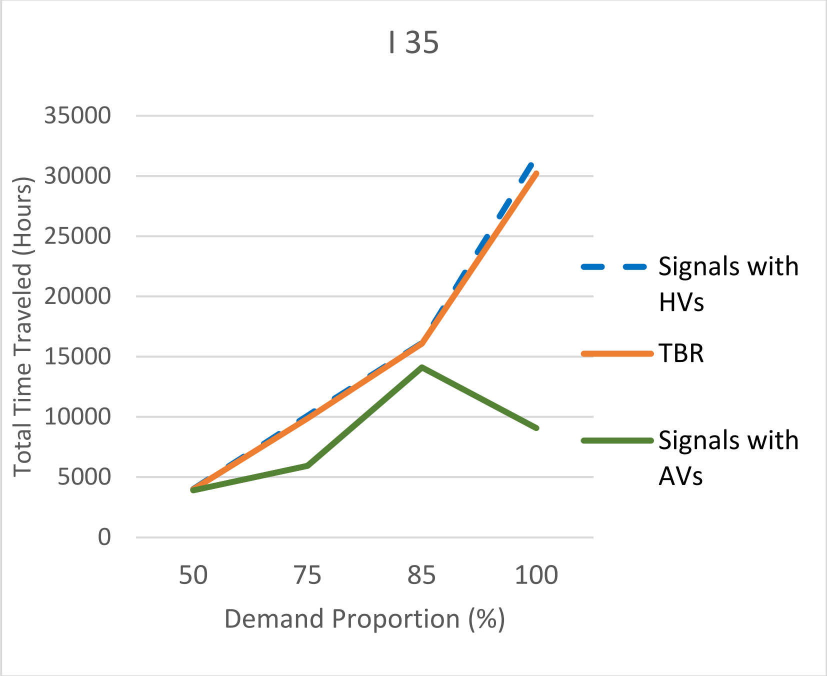


Figure 3: Freeway network travel time results for I-35

STA simulations were used to observe the effects of having more classes of CAV users with different values of travel time (VOTTs) and to see if there is any change in demand for these trips. As more travelers gain access to CAVs, the travel time (or "cost") per trip generally falls. Predictions indicate that transit demand will fall significantly because travelers can avoid parking costs through repositioning. Parking demand also decreases as travelers seek to avoid parking costs, and space used for downtown parking can be reallocated.

An integrated, agent-based SAV simulation in the DTA model was undertaken as part of TxDOT Project 6847[4]. SAVs were found to result in greater travel times because SAVs must reposition to reach the next traveler, increasing the number of vehicle trips. However, when dynamic ride sharing was used, a small number of SAVs was needed to provide service to all travelers in the simulated network, making overall travel times competitive with those of the personal (privately owned) CAV scenarios. This is because with a small number of SAVs, and most travelers destined for geographically similar zones in the downtown region, each SAV could carry three or four travelers per trip. Therefore, SAVs with dynamic ride sharing could be both cost-effective and provide a reasonable level of service to travelers.

Potential Emissions Benefits of CAV Use

In addition to the potential influences of CAVs on mobility and safety, CAVs are also expected to have significant impacts on the sustainability of transportation systems. CAV driving profiles, a diagram of a vehicle's speed as time progresses, are anticipated to be smoother. This smoothing

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[4] Detailed documentation for Project 0-6847 will be available in the final project report, with publication likely in 2017. Project details and deliverables are provided in the CTR Library Catalog: http://ctr.utexas.edu/library/.

effect is referred to in practicality as "Eco-Self-Driving" behavior of CAVs, because CAVs are expected to have improved reaction time and vehicle maneuvering capability. Normally, the large (and sometimes frequent) fluctuations of human driver speeds are the result of slow reaction times (typically, 1.5 to 4 seconds). With CAV technologies, fluctuations are expected to be rare, resulting in smoother driving profiles—the Eco-Self-Driving (ESD) cycles.

Project 0-6847 explored the environmental impacts of CAV use (Liu et al. (2016)). Using the EPAs MOVES model different emission rates and levels were calculated for CAVs and compared to emission rates produced from conventional HVs. Because of the smoothed driving profiles, CAVs tend to have lower emission rates for all the different pollutants tested. A typical driving profile of an HV is shown in Figure 4.

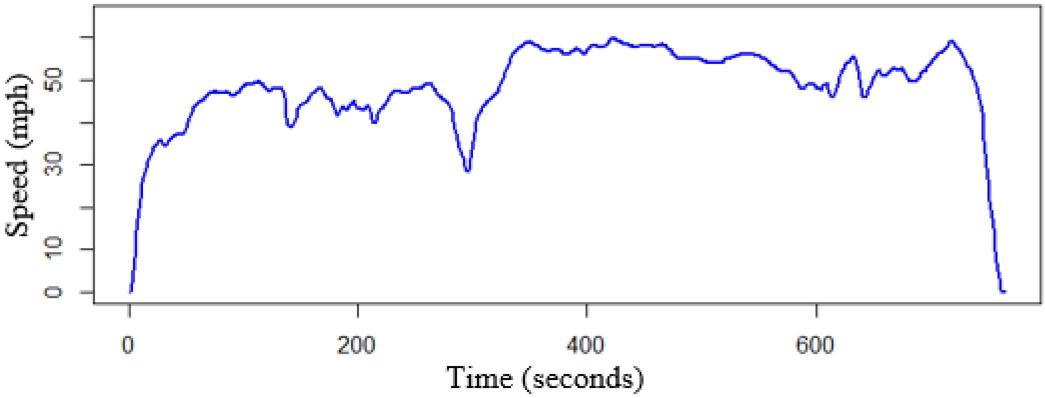

Figure 4: Typical Driving Cycle for Human-Driven Vehicle

It is anticipated that smoother driving cycles for CAVs will occur (thanks to better vehicle awareness and throttle control). Figure 5 shows an example of a typical driving cycle for an HV compared with a smoothed driving cycle. The spline smoothness factor is a measure of the smoothing effect of the cycle.

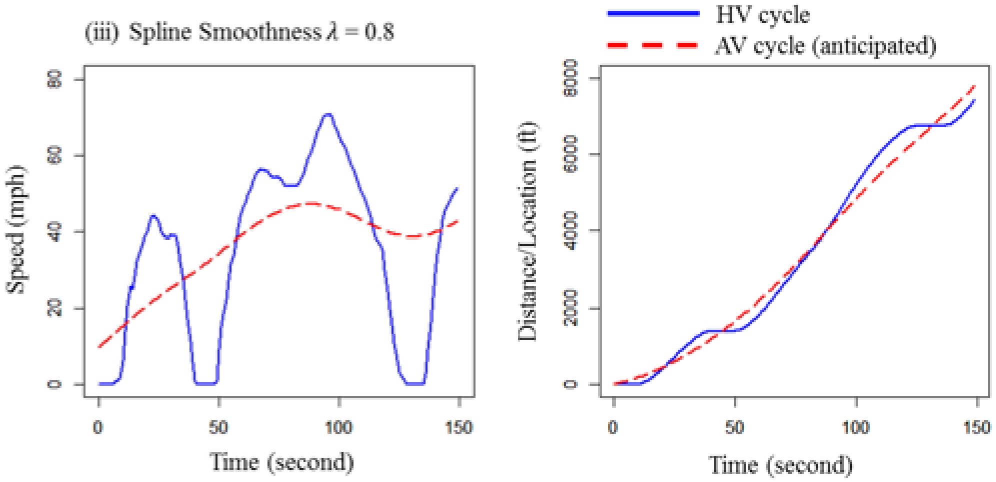

Figure 5: Original HV Driving Cycle vs. Smoothed AV Driving Cycle

Estimates for CAV emission impacts, relative to HV values, using the EPA MOVES model were developed. EPA and Texas A&M Transportation Institute cycles were smoothed to obtain the

CAV ESD cycles for national and local emissions estimates. Five emission types were considered in the estimation: fine particulate matter (PM2.5), carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO_2), and carbon dioxide (CO_2). The emission results were compared between the original cycles (for HVs) and smoothed cycles (for CAVs). Differences in these values suggest a likely environmental impact of CAVs, assuming they are programmed to drive more thoughtfully than human control.

The results from EPA cycles showed that, in general, the smoothed CAV cycles deliver lower average emission rates (per cycle, in grams per average mile of travel) across all five emission species. Therefore, the CAVs are expected to have positive impacts on the environment relative to HVs. Further, the CAV cycles that were smoothed based on HV cycles with hard acceleration and braking events were likely to create an even lower average emission rate. The results indicate that if HVs are replaced by CAVs, greater emission benefits (up to 25% emission reductions) are anticipated in driving conditions where there are many hard acceleration and braking events, and also for drivers with aggressive driving styles. It is important to note that these emission levels were tested assuming the same amount of demand, which is measured by total number of miles driven, for both the before and after cases. Increased demand from CAV use may negate the potential environmental benefits from smoother CAV driving. However, this increase in demand was not considered so that the effect of smoother drive cycles could be isolated and examined thoroughly.

Using data for Austin, the results from Austin cycles were consistent overall with emissions based on EPA cycles. Lower average emission rates were revealed for smoothed Austin cycles as compared with the original cycles. The mean emission reductions were found to be 16.28% for PM2.5, 9.77% for CO, 10.86% for NOx, and 3.72% for SO_2 and CO_2. Simple regression models were constructed to explore the correlates of the emission reductions with fuel type, vehicle type, temperature, and link-level average speed. CAV passenger cars were found to be associated with lower average emission rates of PM2.5, CO, and NOx than passenger trucks. Diesel vehicles were linked with smaller emission reductions for these three types of emissions. The road links with higher average speeds had greater emission reductions for all five types of emissions.

Planning Implications of CAV Use

Another aspect that planners must anticipate from future CAV use is the induced vehicle miles traveled (VMT). CAVs are anticipated to lead to increased VMT since driving becomes easier: essentially, drivers experience falling travel time burdens (the lowered VOTT makes vehicle use less “costly”) so they are comfortable heading to more distant locations (or replacing air travel with highway travel). Additionally, those formerly unable to drive (such as those with disabilities) are able to navigate in a motorized vehicle safely, some vehicles are sent around empty (to pick up the next passenger or park), trucking becomes more cost-competitive (relative to rail, due to lowered driver needs), and latent demand for road use will emerge on roadways whose congestion levels fall (due to better car-following and/or fewer traffic incidents). SAVs may also emerge as a new transportation mode, with such vehicles acting as driverless taxis or shuttles. SAVs may ultimately lead to fewer privately owned vehicles, particularly in urban areas, as individuals come to rely on SAVs for much of their travel needs. Nonetheless, it will be important for TxDOT to plan for this anticipated increase in demand on Texas roadways from CAV use.

Risk compensation is another issue to consider when systems are improved. For example, soon after cruise control was introduced, the crash rate increased as that convenience allowed 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 choices by users who cannot currently operate a vehicle due to disability, as well as the choices made by pedestrians and bicyclists. 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. Planning models will need to take these types of impacts into account, with trip, mode, and route choice models being modified to include the effects on safety behaviors, including risk compensation.

Section 4. Potential Safety Strategies for TxDOT to Adopt to Prepare Texas for CAV Use

The transition from HVs to CAVs will certainly benefit the state of Texas but will also present challenges to be addressed. 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 feel are of importance to ushering in CAV use. The strategies are 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.

Short-Term Strategies

In the short term, 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 amount 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

Medium-Term Strategies

In the medium term, 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 rules of road

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, shared autonomous vehicles (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 of empty driving

It is important to note that SAV use is expected to increase total system 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' VOTT, 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 global positioning system (GPS) tracking and radio frequency identification (RFID) tags should be explored. Traditional schemes are more feasible for longer corridors with higher levels of congestion.

Long-Term Strategies

Long-term strategies 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 automated vehicles. 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.

Section 5. Best-Practice Recommendations for TxDOT in Deployment of CAVs in Texas

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 (CICAS) 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.

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.

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.

References

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Appendix A: Catalogue of Automation Technology Packages

Technology	**Automation Level**	**Purpose**
Forward Collision Warning	Level 0: No Automation	Provide warnings to driver of impending forward collision
Blind Spot Monitoring		Provide warnings to driver of objects in his or her blind spots
Lane Departure Warning		Provide warnings to driver when vehicle drifts out of lane
Traffic Sign Recognition		Detect and notify driver of approaching signs and current speed limits
Left Turn Assist		Provide warnings to driver of an impending unsafe left turn
Pedestrian Collision Warning		Provide warnings of impending collision with pedestrian
Rear Cross Traffic Alert		Provide warnings of impending collision with crossing vehicles when reversing
Adaptive Headlights		Headlights that adjust to follow curved path more accurately
Adaptive Cruise Control	Level 1: Function Specific Automation	Sensors help maintain a proper following distance in conjunction with cruise control
Cooperative Adaptive Cruise Control		Wireless communication used mutually between cars to minimize headways in conjunction with adaptive cruise control
Automatic Emergency Braking		Automated braking used in response to impending collision as a preventative measure
Lane Keeping		Sensors detect pavement markings and automated steering assistance keeps vehicle centered in lane
Electric Stability Control		Automated braking assistance used to minimize sliding in the event of traction loss
Parental Control		Speed limitations and volume control to help create safer driving experience for young drivers

Technology	**Automation Level**	**Purpose**
Traffic Jam Assist	Level 2: Combined Function Automation	Adaptive cruise control and lane centering in low-speed conditions such as stop-and-go traffic
High Speed Automation		Adaptive cruise control and lane centering at speeds higher than stop-and-go traffic conditions
Automated Assistance in Roadwork and Congestion		Longitudinal and latitudinal driving assistance in construction zones
On-Highway Platooning	Level 3: Semi-Automation	Automated driving along a link in platoons with small headways
Automated Operation for Military Applications		Level 3 automation in military outfitted vehicles
Self-driving car	Level 4: Full Automation	Completely autonomous vehicle that has 100% of driving responsibility
Emergency Stopping Assistant		Allows shutdown of driverless vehicle in case of emergency
Automated Valet Parking		Driverless parking completed by vehicle with the assistance of a smartphone app