PRODUCT 0-6847-P1

TXDOT PROJECT NUMBER 0-6847

BEST PRACTICES FOR MODIFYING TRANSPORTATION DESIGN, PLANNING, AND PROJECT EVALUATION IN TEXAS

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DECEMBER 2016; PUBLISHED MARCH 2017

http://library.ctr.utexas.edu/ctr-publications/0-6847-P1.pdf

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TxDOT Project 0-6847: An Assessment of Autonomous Vehicles: Traffic Impacts and Infrastructure Needs

December 2016; Published March 2017

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

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Introduction

Connected and automated vehicles (CAVs) in Texas are about to significantly change how the Texas transportation system works. The Texas Department of Transportation (TxDOT) maintains the most widespread state-level transportation network, and it is important to expect, understand, and respond to the increasing number of CAVs that are expected within the next few decades. The UT Austin Center for Transportation Research (CTR) has conducted research into the effects of CAV market penetration. This research informs the changes and responses that are expected when concerning the design and planning of future projects, as well as evaluating the effectiveness of projects.

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. These tenets summarize the magnitude of what's at hand:

- Private industry and academic research are developing automated technologies at a rapid rate. Public partnership around policies, standards, and infrastructure investments are crucial for realizing the fullest potential of CAV technologies in terms of safety, traffic operations performance, and environmental impact.
- Another benefit to TxDOT from good partnerships, policies, and investments is the potential savings in infrastructure costs. While CAVs may require some public investment, CAVs implementations may reduce the need to design and construct additional roadway capacity.
- The future can be looked at in terms of short-, medium-, and long-term outlooks. While the short-term goals respond to technologies entering our roadways today, the long-term outlook is needed for better informing today's future-facing planning efforts.
- While the driving emphasis in the short term may be on improving safety, the longer-term emphasis may branch to improving reliability.
- All stages of CAV market penetration can lead to significant benefits. However, without sufficient public policy, an increased introduction of CAV technologies actually has the potential to significantly *worsen* traffic conditions and energy usage from that of today.
- For TxDOT to best address the introduction of CAVs from a modeling and design perspective, TxDOT's design manuals must be updated to accommodate the capabilities of new technologies. Further research is needed to inform design specifics.
- The expertise of operations personnel and field technicians within TxDOT and municipal traffic operations organizations needs to be expanded if these organizations are to reliably understand and integrate technology into the future infrastructure. Likewise, the design questions at hand around CAVs will be inherently more complex than many of today's design activities.

This guidebook is a desktop guide for TxDOT staff to facilitate an understanding of 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.

This guidebook is organized as follows. First, Chapter 1 introduces a broad overview of automated technologies and when these technologies are expected to enter the market, with discussions on public perception and legal responses that are appropriate for those times. Next, Chapter 2 explores further analysis results on gradual levels of CAV and shared AV (SAV) market penetration, and looks at the benefit/cost of advanced CAV technology deployment. With the prior analysis, Chapter 3 covers the implications of CAV market penetration on today and tomorrow's modeling, design, and planning activities, while 0 briefly introduces a set of representative field-testing scenarios. Finally, 0 summarizes key recommendations that come from this guidebook, other sources, and general experience among researchers who have performed related project work. Throughout this document there are highlighted experimental observations, assumptions, and recommendations that can all be informative in incorporating automation with future efforts in planning, design, and project evaluation.

Chapter 1 Characterizing CAVs

This chapter introduces CAVs and their technologies. Although some technologies that enable CAV functions exist today, there is still a great deal of development that will happen within the next few decades, both in technology and governmental policy. As these technologies continue to develop, it is imperative to continue research to prepare for their eventual deployment on Texas roadways. Key technologies and their timeline are presented along with the National Highway Traffic Safety Administration (NHTSA) taxonomy of different levels of automation. (Much of this is reproduced from the 0-6849-P1 Guidebook [Kockelman 2016a], which covers technological advances). Then, public perception and market penetration potential are addressed, which informs expectations on how the general transportation system and its users will be affected by an increasing number of CAVs on public roadways.

Technologies

Smart driving technologies have drawn significant attention in recent years, due to their rapid development and potential safety, mobility, and environmental benefits (Litman, 2015). 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.

Taxonomy

In 2013, NHTSA released a "Preliminary Statement of Policy Concerning Automated Vehicles." NHTSA regularly provides definitions of different levels of automation 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 (AVs)* refers specifically to "those in which at least some aspects of a safety-critical control function (e.g., steering, acceleration, or braking) 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 (e.g., 3 seconds) transition (or "handoff") 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, or **automatic braking** (dynamic brake support and crash imminent braking), or lane-keeping, and/or 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 trip.**	***System will perform all the monitoring.***	**Driverless car**

Key Capabilities

To clarify the scope of CAV technologies, this guidebook uses NHTSA's four-level automation taxonomy. 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. L4 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, forward collision warning, and automated emergency braking.
4. Adaptive cruise control
5. Dynamic route guidance and data sharing

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 0-6838, a related research project helmed by CTR. 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, and 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.

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

Automation Level	Technology	Maturity Time Frame	Major Safety Benefits	Maturity	TxDOT Involvement
Level 0: No Automation	Forward collision warning	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
Level 1: Function Specific Automation	Adaptive cruise control	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

Automation Level	Technology	Maturity Time Frame	Major Safety Benefits	Maturity	TxDOT Involvement
Level 2: Combined Function Automation	Traffic jam assist	Medium	Driving assist	Medium	Policy
	High speed automation	Medium	Driving assist	Medium	Policy
	Automated assistance in roadwork and congestion	Medium	Driving assist	Medium	Policy
Level 3: Semi-Automation	On-highway platooning	Long	Driving assist, prevent rear-end crashes	Medium	Policy
	Automated operation for military applications	Long	Prevent human fatalities	Low	Policy
Level 4: Full Automation	Self-driving vehicle	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

The timeframe of "short," "medium," and "long" may be roughly equated to these ranges:

- **Short:** Up to Year ~2021
- **Medium:** Year ~2021 through ~2031
- **Long:** Year ~2031 and beyond

Considering this range of timeframes is important in many of today's design efforts.

Considerations

- One area worth further investigation, as CAV technologies are introduced, involves the participation of drivers through use of personal electronic devices. For example, a smartphone app or virtual reality headset that runs on a personal device in the vehicle can be used to receive and transmit DSRC signals from and to other connected vehicles (CV); it may also be used in conjunction with low-cost radar and video cameras to warn drivers if an approaching obstacle (like a slowing lead vehicle or a bicyclist on the side) is being detected. Adding "intelligence" and communication capabilities to existing, conventional vehicles and/or their drivers via low-cost technologies can dramatically accelerate the market penetration transition of warning technologies—well beyond what can be delivered off of manufacturers' assembly lines for new vehicles.

- Related to this is the manufacture and use of a portable onboard devices (PODs), which are self-contained detection and warning systems that can be added into existing vehicles. DSRC-communicating roadside devices or roadside equipment (RSEs) can be deployed and maintained by the state DOT. PODs and RSEs provide communication and connectivity for previously unequipped vehicles and infrastructure, adding value to and thus speeding up adoption of CV technologies, via rather simple and cost-effective retrofits of conventional vehicles. At some point and in certain locations, such retrofits may become mandatory.
- Although POD-type technologies will exist for making conventional vehicles connected, the prospect of retrofitting older vehicles into self-driving or even self-braking vehicles is likely to be prohibitively expensive.

For further details on each of the capabilities identified, please see TxDOT Project 0-6847 Final Report (Kockelman 2017).

Convergence

As vehicle automation and communication technologies continue to develop, they are expected to converge, enabling new cross-cutting synergistic applications. Individually, each of these technologies has its own limitations. For instance, CV systems may offer suggestions and provide warnings to help improve safety; however, with human drivers still in control, many errors may simply be unavoidable (e.g., crashes caused due to driving under the influence, aggressive driving, inexperience/over-correction, etc.). Moreover, even if a CV provides a suggested course of action (e.g., a safety suggestion or better route to avoid congestion), the information is useless when the driver opts against following the suggestion. With AV technologies, optimal safety and routing decisions can be made, but without connectivity those decisions are effectively made in isolation, only in reference to what the individual AV can observe.

As AV and CV technologies converge within individual vehicles, new capabilities will be enabled. Connectivity and automation can work together to enhance both safety and mobility. Vehicle-to-infrastructure (V2I) or vehicle-to-vehicle (V2V) communication can effectively serve as an extra sensor on board an AV, delivering more precise information regarding the world around it, and the actions being taken by vehicles and infrastructure. Moreover, working together, AV and CV technologies can enable new mobility-enhancing opportunities, such as speed harmonization, intelligent signal control, intelligent ramp metering, and dynamic route guidance. These and other strategies can be used to more effectively improve traffic flow and operations, thus delivering congestion improvements to CAVs and non-CAVs alike.

Driving Forces and Public Perception

AVs have the potential to fundamentally shift the paradigm of driving, by offering an array of safety and driver-assistance features. These features will directly benefit drivers in various ways, and therefore, the public will be interested in purchasing cars with smart driving technologies. First and foremost, AVs can substantially reduce or mitigate crashes. Second, smart driving technologies will free drivers from driving tasks, and thus reduce their stress, especially in congested traffic that is recurrent. Third, they can provide critical mobility to captive riders (e.g., those too young to drive). Fourth, they have the potential to increase road capacity, save fuel, and lower emissions per vehicle-trip, if automatic steering and speed algorithms are carefully developed. Complementary trends in shared rides and vehicles may lead us from vehicles as an owned product to an on-demand service, and mitigate the need for parking space and change land use patterns, including changes to current zoning codes that often require specific parking requirements per occupant or dwelling type. However, making motorized travel easier (while allowing some vehicles to travel empty) may also result in significant vehicle-miles traveled (VMT) increases, resulting in much worse congestion and higher emissions overall. Society should proceed with caution, ensuring thoughtful policies and practices are in place (e.g., credit-based congestion tolls via GPS at all locations, caps on fleet-managed empty driving, and strict limitations on empty driving by privately maintained vehicles).

Safety

CAV technologies are expected to confer considerable safety benefits by reducing both crash rates and injurious outcomes. Perceptions include protection from drunk drivers, reduction of wrong-way driving, and an improved ability to avoid collisions with pedestrians and bicycles. Even with a traffic network that has human-operated vehicles mixed with AVs, safety improvements are to be realized among both human and CAV drivers. Later sections in this document, as well as the 0-6849 Guidebook (Kockelman 2016a), offer additional material on safety benefits

Productivity

One of the most highly valued benefits CAVs offer is a less burdensome travel experience for drivers, effectively reducing their value of travel time (VOTT). VOTT is defined as an individual’s willingness to pay to avoid another hour of travel. If an individual is able to both reduce stress and increase productivity while traveling by becoming a passenger (rather than being forced to maintain focus on driving), his/her VOTT falls. This makes CAVs relatively attractive for current drivers, if not for current passengers. Moreover, simulations show that CAVs will eventually increase lane and roadway capacity, or network productivity, by reacting faster to changes in preceding vehicles’ speeds and positions. Technical competence and rising confidence in CAV response times can lead to shorter following distances and headways between vehicles. Parking costs for CAVs may also fall, since AVs may be able to drop off their passengers and seek lower-cost parking elsewhere, or otherwise serve someone else’s trip-making needs.

Consideration

For purposes of benefit-cost analyses, VOTT for light-duty/personal vehicles may be assumed to be just $8.90 per driver-hour, approximately half of the 2014 median wage rate in Texas (according to the U.S. Bureau of Labor Statistics). Benefits from added productivity and leisure, due to self-driving vehicles relieving drivers of the driving task, may then be assumed to be 50% of the travel time valuations of Texas drivers, or $4.95 per hour, to avoid driving one’s vehicle.

In work related to this guidebook, researchers conducted a random survey of Texans. This survey asked the respondents what their willingness to pay (WTP) to save 15 minutes of travel time. After excluding the respondents who answered $0, the average WTP of 1,364 Texans was $9.50 per 15 minutes. Scaling this value to an hourly basis, the average VOTT was $27.20/hour—much higher than assumptions based on wage rates. Increasing the VOTT parameter increases the estimated benefits of driving-task reduction.

Once car travelers are freed from the driving task, the passenger compartment may be transformed: former drivers may be working on their laptops, eating meals, reading books, watching movies, and/or calling friends—safely. It is estimated that, by 2030, the value of the global automated-car market will be worth $87 billion (LUX Research, 2014).

Socioeconomic Barriers and Benefits

A number of barriers are anticipated to challenge the development and implementation of intelligent driving technologies, especially the Level 3 and Level 4 technologies. The major factors that could hinder technology adoption before its full maturity include the following:

- **Added Costs:** Compared to a conventional car, the Level 0 (CV) and L2 technologies incur extra cost, ranging from several hundred to thousands of dollars. For example, an intelligent driving package—including radar-based adaptive cruise control, collision warning, and adaptive braking costs—about $1,200. This cost is even higher on L3 and L4 vehicles, because a Lidar system (as used on Google's driverless car) alone costs thousands of dollars, even under coming mass production.
- **Security and Privacy:** When vehicles are controlled by computers and connected wirelessly, like other cyber-physical systems, they are vulnerable to attacks, including hacking, and GPS spoofing. Meanwhile, with the smart driving technologies, a large amount of data is generated and collected, through onboard sensors. These data contain location information that could be sensitive, e.g. where a car was last parked and distances traveled as well as time and speed.
- **Long Transition Period:** It is anticipated that when smart driving technologies are adopted, there will be at least two more decades where rather conventional vehicles still use the nation's roadways. Average operating life of model year 1990 cars is/was 16.9 years, and NHTSA data on light-duty vehicle survivability suggest lifetimes have been rising (Lu 2006). Many travelers may hesitate in letting go of private ownership in exchange for sharing vehicles and sharing rides with strangers, especially if technology costs are low. When cars of different automation levels co-exist on the road, the problem of how to manage them and ensure equity, efficiency, and safety will be paramount.

Despite these barriers, CAVs and especially SAVs are poised to allow those who were formerly unable to drive to navigate the transportation network. Accessibility can be improved for shopping, employment, and medical appointments. Such impacted social groups include children, the elderly, and disabled persons.

Energy Usage and Emissions

In addition to the potential influences of CAVs on mobility and safety, CAVs are expected to have significant impacts on the sustainability of transportation systems. The driving profile-a diagram of a vehicle's speed as time progresses-of a CAV is anticipated to be smoother. This smoothing effect is referred to as the "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 (Liu and Kockelman, 2016).

Additional factors that affect energy consumption in the introduction of AVs include congestion mitigation, platooning, lightening/streamlining vehicle features from an emphasis on performance to an emphasis on economy, and crash avoidance (Wadud 2016). Although many assumptions are made today about the potential for reduction in emissions precipitated by a high penetration of CAVs, performance can actually be significantly worse if certain criteria are met, including a dramatic overall decrease in VOTT leading to an increase in VMT, and stalemates on government policy that could otherwise regulate, encourage, and incentivize sustainable and economical CAV system design. Nearly all pertinent laws and legal requirements governing auto safety and transportation were passed decades before the development of CAVs. Therefore, it is important to identify guiding assumptions when anticipating future energy use and emissions.

Legal Implications

Numerous public benefits are associated with CAVs, but these technologies also present risks and challenges for our transportation system. Presently, the legal landscape for CAVs is one of much uncertainty and flexibility. 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.

The 0-6849 Guidebook (Kockelman 2016a) identifies key legal implications of CAVs that should be addressed by state and sometimes local governments. In short:

- Pertinent laws and legal requirements governing auto safety and liability were passed decades before the development of CAVs.
- Some liability may fall on a government agency or private vehicle operator for the malfunctioning of CAVs, in both testbed environments and the field.
- Data breaches and hacking incidents can also result in liability for agencies, operators, and OEMs.

The following outlines legal issues that specifically pertain to design, planning, and evaluation of future transportation systems:

- Liability to a government agency for malfunction of infrastructure. The redundancy and resiliency of infrastructure (especially electronic infrastructure) carries implications for design and planning. To assess the significance of liability, agencies and investigators should perform further research in quantifying the likelihood and effects of malfunctioning or failed infrastructure.

- Planning for the excessive demand that comes with empty-driving CAVs versus requiring CAVs to be occupied for all or a percentage of all driving time.
- Assessing the extent to which SAVs are allowed to drive empty, which also has planning implications, both for infrastructure capacity and the government's involvement in encouraging and regulating the operation of SAVs.
- Determining and responding to the government's responsibility for providing quality data and other communications that facilitate the use of CAVs and transportation system in general (this falls under the notion of "data governance," a continually emerging area that is necessitated by challenges surrounding the general explosion of data availability within the field of transportation).

Related to this, Hedlund's (2017) recent report for the Governors Highway Safety Association discusses top legal and licensing issues for state DOTs, departments of motor vehicles, and associated agencies. The report arrives at the following major recommendations (with associated details) for state transportation officials: *be informed*, *be a player in your state*, *understand the role of states*, *don't rush into passing laws or establishing regulations*, and *be flexible*. These are valuable to keep in mind for all stakeholders.

Mainstream Adoption Timetable

Level 0 and Level 1 technologies are already entering mainstream adoption, with many technologies readily available (e.g., blind spot monitoring) on many passenger vehicle makes and models or mandated (e.g., electric stability control) across all new vehicles sold. Barriers for such technologies are mainly cost, reliability, and legislation (e.g., rules regarding adaptive headlight use in the United States). As such barriers are overcome, one expects that market penetration of these technologies will increase rapidly. Level 2 technologies also have high potential for the near future, with features such as adaptive cruise control in conjunction with lane centering or lane keeping assist gaining momentum. Level 2 technologies involve fewer human factor complications than Level 3 and Level 4, and their major impedance is cost, which will fall over time. In contrast, Level 3 and Level 4 technologies face the greatest barriers to adoption, due to uncertainty in their performance under real-world driving, along with cost (for cameras, Lidar, computers running very specialized software on board, and other fail-safe hardware and software requirements). This is due both to the reliability of these technologies (e.g., driverless controls in extreme conditions, such as heavy rain or strong roadway glare), and to human factors especially in Level 3, when a driver is expected to retake control of the vehicle quickly (e.g., under 3 seconds) and drive properly immediately. Legislative considerations and cyber-physical threats also pose significant challenges to large-scale market penetration, since liability issues remain unresolved and the potential for hacking vehicle computer systems persists. Table 3 lists main barriers, summarized by technology, along with the predicted interval of substantial adoption.

Table 3: Forecast of Technology Development Timeline

#	Technology	Mainstream adoption	Barriers
1	Forward Collision Warning	2015–2020	Reliability
2	Blind Spot Monitoring	2015–2020	Cost
3	Lane Departure Warning	2015–2020	Infrastructure
4	Traffic Sign Recognition	2015–2025	Cost, Technology Maturity
5	Left Turn Assist	2015–2025	Cost, Infrastructure
6	Adaptive Headlight	2015–2020	None
7	Adaptive Cruise Control	2015–2020	Cost
8	Cooperative Adaptive Cruise	2020–2025	Standard, Cyber-security
9	Automatic Emergency	2015–2025	Cost, Reliability
10	Lane Keeping	2015–2020	Infrastructure
11	Electric Stability Control	2010–2011	None; mandated by NHTSA since 2012 model year
12	Parental Control	2015–2020	None
13	Traffic Jam Assist	2015–2020	Cost
14	High Speed Automation	2015–2025	Reliability
15	Automated Assistance in Roadwork and Congestion	2015–2025	Infrastructure, Reliability
16	On-Highway Platooning	2015–2020	Infrastructure, Cost
17	Automated Operation for Military	Unknown	Unknown
18	Driverless Car	2015–2030	Regulation, Liability, Cost, Cyber-security, Infrastructure
19	Emergency Stopping	2015–2025	Liability
20	Auto-Valet Parking	2015–2025	Infrastructure

Potential Safety Strategies

The transition from human-operated vehicles to CAVs will present challenges as well as benefits. 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.

For more information on each of these strategies, refer to the 0-6849 Guidebook (Kockelman 2016a).

Short-Term (Up to Year ~2021)

- **Better road markings** to facilitate lane departure warning, traffic jam assist, and platooning.
- Travel demand modeling staff learn to use and then apply **agent-based demand-forecasting models** of travel demand, empty-vehicle travel, and traffic.
- **Signage development for CAVs** that detect and interpret road signs.
- **Shaping legislative policy on CAVs** to ensure oversight for developing CAV technologies.

Medium-Term (Years ~2021 through ~2031)

- **Construction/detours methodology** for rerouting CAVs as necessary
- **Lane management**, which includes the introduction of CAV-only lanes on freeways and city streets
- **Nighttime rules of road** for CAVs that may differ from that of day, for improving operations and safety
- **SAV integration** for facilitating optimal operation of shared automated vehicles
- Developing and enforcing regulations of empty driving to significantly limit congestion
- **Roadway design amendments (within TxDOT manuals)** to incorporate CAV-specific infrastructure design requirements
- **Tolling and demand management** for alternative revenue generation and congestion control

Long-Term (Year ~2031 and Beyond)

- **Construction and maintenance design** that pertains to the automation of construction, incident response, surveying, etc. vehicles
- **Rural signage and rural road design** to transition CAVs from urban environments
- **Smart intersections** (e.g., reservation strategies) for optimizing intersections to a much greater extent than is possible with today's traffic signal operation strategies
- Credit-based congestion pricing becoming universal

Traffic Impact

In general, AVs can reduce travel times through crowd-sourcing-based navigation (smarter route choices), automatic collision reports (e.g., OnStar), cooperative adaptive cruise control, smoothed drive cycles, and more stable cruising speeds. AVs can also reduce travel time uncertainties via better en-route information (such as construction, incidents, weather events, etc.) and choices, dedicated lanes, and less traffic flow breakdown. It is anticipated that they can increase lane and intersection capacity and smooth traffic oscillations in two main ways:

- **Lane capacity:** AVs can use shorter headways through auto-platooning or cooperative adaptive cruise control (CACC) and/or lane centering (in narrower lanes), which translates to higher capacity (1 to 80% increases in effective capacity, with adoption of 10 to 90% CACC).
- **Intersection capacity:** AVs and CVs can anticipate green phases of light cycles, making better use of signal time. They can be better coordinated and share scarce intersection space via mini-platoons based on reservation instructions, for specific paths through an intersection at specific times (up to 95.5% delay reduction as adoption rates hit 100%).

The implications of AVs in altering lane and intersection capacities will necessitate revision of existing TxDOT design manuals.

Apart from CAVs, SAVs can also influence passenger flows, fleet size, and consequently the need for parking spaces:

- **Passenger/person flows:** Smarter vehicles and trip requests can be matched in real time, increasing vehicle occupancies through dynamic ride-sharing (from U.S. current average of just 1.55 persons) and reducing traffic congestion (by reducing VMT per person-mile travelled)
- **Reduced fleet sizes and lower parking demands:** shared driverless fleets are estimated to reduce the demand for vehicles in urban areas by 90% (among carsharing fleet members); this will reduce parking loads, freeing up street space for other modes or additional lanes, in some settings.

Intersections and Vehicular Interaction

The introduction of AVs brings about many opportunities for new approaches for controlling intersections, and other situations where vehicles interact with each other in occupying the same section of roadway. A *reservation*-based intersection control allows for the coordination of traffic entering an intersection without the use of traditional traffic signals. Reservation control schemes may incorporate communications among multiple vehicles that lead to a general, system-wide optimization of a traffic system, as seen in Chapter 3. One outcome of some reservation control schemes is the intermixing of directional and turning traffic in ways that carry many more intermixed movements than that seen by the split/phase approach of traditional traffic signals.

Considerations

- It is possible to consider the use of designated lanes for CAVs within a reservation-based intersection. This may offer some efficiencies for various movements.
- Additional capacity at stop-sign controlled intersections will be gained by not requiring CAVs to not fully stop if it is safe for the vehicle to proceed through the respective intersection.

- Because of the precision expected from advanced CAV technologies, further roadway capacity may be recovered by narrowing AV-only lanes from that of standard road designs.

Infrastructure Needs

Based on the previous literature synthesis on smart driving technologies, the team created Table 4, which predicts potential infrastructure needs.

Table 4: Infrastructure Needs Evaluation for Different Technologies

Technology	Automation Level	Maturity	TxDOT Involvement
Forward Collision Warning	Level 0: No Automation	H	P
Bind Spot Monitoring		H	P
Lane Departure Warning		M	Y
Traffic Sign Recognition		M	Y
Left Turn Assist		M	Y
Adaptive Headlight		H	N
Adaptive Cruise Control	Level 1: Function-Specific Automation	H	P
Cooperative Adaptive Cruise Control		M	Y
Automatic Emergency Braking		M	N
Lane Keeping		M	Y
Electric Stability Control		H	Y
Parental Control		M	P
Traffic Jam Assist	Level 2: Combined Function Automation	M	P
High Speed Automation		M	P
Automated Assistance in Roadwork and Congestion		M	Y
On-Highway Platooning	Level 3: Semi-Automation	M	P
Automated Operation for Military Applications		U	N
Google's Driverless Car	Level 4: Full Automation	L	P
Emergency Stopping Assistant		H	P
Automated Valet Parking		L	Y
Notes: H=high, M=intermediate, L=low, U=unknown; Y=yes, N=no, P=possible.			

Many smart driving technologies are decentralized, in the sense that they do not require any communication with the infrastructure (i.e., V2I) to work. In general, under normal operational conditions, certain smart driving technologies—e.g., lane departure warning and lane keeping—will require clear lane marking and traffic signs, because they rely on sensing these objects to determine the surrounding environment. Other technologies, such as adaptive cruise control and blind spot monitoring, do not require particular infrastructures, because these are vehicle-based features that only rely on sensing of surrounding vehicles but not particular infrastructure. The technologies that will require the most infrastructure changes are traffic sign recognition, automated assistance in roadwork and congestion, auto-valet parking and driverless cars.

Recommendations

- To identify what roadside CAV infrastructure TxDOT will be responsible for, considerations will need to be made for the maintenance and reliability of this equipment. This will need to cover factors including equipment theft and malfunction. Part of the work ahead will be to incorporate infrastructure reliability into planning and project evaluation.
- In general, intersection management strategies (including reservations) are key to a successful transportation system and should be a priority for the Statewide Transportation Improvement Program.

Chapter 2 Effects of Market Penetration

Currently, CAV technologies are still in developmental stages. Vehicles featuring advanced levels of automation are not yet available to the public, and CAVs are too expensive for most people to consider buying. As these technologies develop further, prices will fall, benefits will be more widely understood, and people will make the switch to CAVs. While 100% CAV penetration is unlikely in the next 25 years, the rising CAV use on U.S. roadways is almost certain. Therefore, understanding how different levels of CAV penetration among travelers can affect others is important.

Analysis of market penetration can also be beneficial in creating economic forecasts that are relevant to auto industries and other supporting industries. It is anticipated that CAV market penetration will significantly impact such forecasts and outcomes.

Introduction of the Analysis

The two arterial networks, three freeway networks, and one downtown city network that were used for research related to this Guidebook are among the top 100 congested roadways in Texas. Segments and areas were chosen so that the results would be widely applicable; however, there are features unique to each area that may not convey to other locations.

In the downtown city network, static assignment was performed with automobile, bus, and walking modes with VOTT ranging from $1.15 to $22 per hour across 10 classes of transportation users. (Recall that VOTT varies with socioeconomic class, so a spectrum of VOTTs are analyzed.) The effects of increasing CAV ownership were then studied. See the 0-6847 Final Report (Kockleman 2017) for further details on the methodology and analysis.

Transit

Simulation outcomes showed a decrease in transit demand as more VOTT classes receive access to CAVs. Transit demand is high without CAVs because a high proportion of low VOTT travelers, choose transit. Travelers with high VOTT are more likely to choose to drive their own vehicles. Therefore, when CAVs are available only to the upper classes, the effect on transit ridership is small. However, as CAVs become available to lower-middle VOTT classes, the rate of decline in transit demand is much greater. Overall, the model ultimately predicts a reduction in transit ridership of 61% due to lower costs of CAVs for low VOTT travelers. CAV round-trip demand was a high fraction of the total personal vehicle demand, reaching 83% at full market penetration.

The mode split changed for each VOTT class before any CAVs and after full CAV availability. Across all classes, total demand for any personal vehicle mode changed from 23,500 person trips to 47,676 trips, and with the shift to 39,592 CAV round-trips, the total number of trips made by personal vehicles rose to 87,275-an increase of 271%. Although many of these additional trips are traveling away from downtown, the network still experiences significant increases in link volume. However, average speed decreases were modest. This conclusion is encouraging because it suggests that the increases in demand are substantially offset by increases in capacity from CAVs.

Summary

- Transit demand decreases as VOTT increases across social classes. As seen later, this significantly increases the total number of person-trips (and thus CAV usage) within a traffic network.
- In this analysis, effects of increases in CAV demand are substantially offset and potentially exceeded by effects of increases in capacity from CAVs.

Congestion

In order to estimate the potential benefits reaped from reduced congestion due to CAV use, the authors made assumptions on the effectiveness of CAV use in reducing congestion. The authors used the 2015 Urban Mobility Report to estimate a baseline level of congestion on freeways, surface streets, and arterials during both peak and non-peak time periods (Schrank et al., 2015).

Due to the expected increase in demand from Level 4 automation, researchers assumed a 20% increase in VMT at the 10% CAV market penetration level (see the 0-6849 Final Report [Kockelman 2016b]). Likewise, a 15% increase and 10% increase in VMT per CAV were assumed at the 50% and 90% market penetration levels, respectively.

Because CAVs may travel with smaller headways, which will effectively increase capacity, latent demand from this capacity increase is anticipated. Demand elasticities of 0.4, 0.2, and 0.1 were assumed at the 10%, 50%, and 90% CAV market penetration levels. These elasticities were measured as change in VMT by non-CAVs with respect to changes in capacity.

There is much debate about the extent to which SAVs will achieve popularity in the future automated trip market. SAVs will be Level 4 AVs belonging not to a single owner but to transportation network companies or some other entity. In this analysis, the authors assumed that half of all CAV trips would be served by SAVs at the 10%, 50%, and 90% CAV market penetration levels.

The expected increases in capacity derive from CAVs' use of CACC, which enables each CAV to communicate with other vehicles on the roadway via dedicated short-range communication (DSRC) so that groups of platoons are formed with smaller headways than currently observed with human-driven vehicles. Additionally, the authors assumed that conventional vehicles were not equipped with a transponder, which allows CAVs to communicate with and utilize conventional vehicles in the formation of platoons. Thus, benefits were only derived from CAVs using CACC with other CAVs. A base link capacity of 2100 vehicles/hour/lane was assumed for the base case (0% CAV). Effective lane capacity was assumed to increase by 50, 325, and 1335 vehicles per lane at the 10%, 50%, and 90% market penetration levels. Assumptions made on the increases in lane capacity at the three market penetration levels due to CACC were consistent with the findings of Shladover et al. (2012).

Within the analysis networks used in this work, when only using traditional signals in their networks instead of new alternative methods of intersection management, there was a 26%, 36%, 45%, and 51% reduction in total travel time at the 25%, 50%, 75%, and 100% market penetration levels. When integrating CAVs into the simulations, the researchers assumed headways of only

0.5 sec for CAVs, which may not be feasible at the lower CAV market penetration levels due to concerns about liability. Additionally, since familiarity with CAVs should grow as more CAVs are adopted on the market, it is reasonable to assume that Texans' comfort with smaller headways between CAVs should increase as well. Thus, within the context of this analysis, the flat reduction in delay on freeways was changed to 10%, 15%, and 20% at the 10%, 50%, and 90% CAV market penetration levels. It should be noted again that this is highly dependent upon AV reaction time, which is currently difficult to predict. It is expected that fully realized and optimized autonomous intersection management should reap further reductions in delay. See the 0-6849 Final Report (Kockelman 2016b) for further details.

For surface streets, arterials, and collectors, delay reduction of 5%, 10%, and 15% were assumed at the respective 10%, 50%, and 90% market penetration levels. These estimates were consistent with those made by Fagnant and Kockelman (2015).

Delay reductions and increases in lane capacities from the introduction of CAVs will significantly alter roadway performance as observed today. Current evaluation tools will need to be adjusted to account for such improvements. As CAVs are introduced to Texas roadways, it will be imperative to monitor behaviors to more precisely determine the magnitudes of these shifts. With increasing CAV market penetration, increased lane capacities will reduce the need to build new capacity to accommodate additional demand. Overall, TxDOT should leverage opportunities for using the increase in capacity to obviate the need for new lanes.

Summary

- The introduction of Level 4 CAVs may cause an increase in VMT.
- Increased network efficiency due to market penetration of CAVs may induce additional system demand. The magnitude of this latent demand is predicted to gradually become less prominent as CAV market penetration increases.
- The extent of the impact SAVs will have is uncertain at this time. Ongoing research should be undertaken to better anticipate and plan for the impact of this new mode as self-driving technology continues to develop and public opinions shift.
- Lane capacity may increase partially because of capabilities enabled by wireless communications and interactions among CAVs. An increase in market penetration significantly increases capacity.

Consumer Costs

In work performed by the research team, purchase price costs for automation and connectivity capabilities were assumed to be $10,000, $5,000, and $3,000 at the 10%, 50%, and 90% market penetration levels. A baseline of Texas' existing 23.88 million vehicles was assumed for calculating CAV benefits and costs per vehicle.

An 11.4-year project life and 10% discount rate were assumed. The relatively high discount rate was used to account for the uncertainty in estimating benefits and costs for CAVs. The project life assumption is based on the average life span of a conventional vehicle.

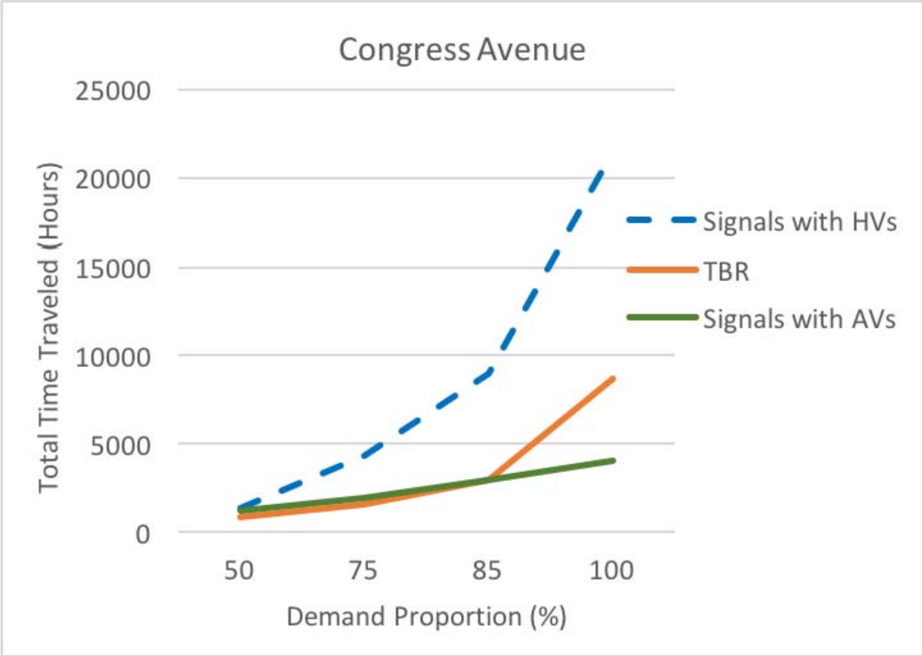
In terms of operating costs, the American Automobile Association (AAA, 2015) estimates the full cost of conventional vehicle ownership and operation to be about $0.60/mile, recognizing depreciation, insurance, maintenance, and operations, and assuming 15,000 vehicle-miles per year in travel. Since CAVs will cost more, their full ownership and operating costs are generally assumed to be $1.00/mile here. Similarly, SAVs' operation costs are assumed to be $1.50/mile under most scenarios.

Networks and CAVs: Travel Times

Travel times through different types of roadway systems will vary as the proportion of CAVs increases. To get a general sense of how CAVs might affect traffic, results are included for freeway, arterial, and downtown networks that were used in research related to this Guidebook. However, results for other regions may vary. For more information on the methodology that produced these results, refer to the 0-6838-2 Report (Kockelman 2016c). In short, the models utilized the cell transmission model (CTM) (Daganzo, 1994, 1995) for routing vehicles within models, and monitored the effects of a first-come first-served (FCFS) policy for tile-based reservation (TBR) intersection control (Dresner & Stone, 2006) that controls movements of individual vehicles through intersections with significantly smaller gaps among conflicting movements than that of traditional traffic signal control.

Arterial Intersections and Corridors

Figure 1 plots travel times at various demand proportions, with various combinations of reduced following headways and intersection controls within a representative model of the South Congress Avenue corridor and a model of Lamar and 38th Street intersection, both in Austin, TX. At all demand proportions, reduced following headways from CAVs improved road and intersection capacity and therefore reduced congestion. The capacity increases affected traffic signals as well; more vehicles were able to travel through each green phase. However, results were significantly mixed for TBR. At high demands, TBR performed well on Congress Avenue, but worse on Lamar and 38th Street. This is because the main bottleneck on Lamar and 38th Street is the intersection between the two arterials. Currently, the traffic signal is timed to give long green cycles to reduce queues. However, the FCFS policy for TBR tends to alternate moving vehicles from each arterial in the interests of fairness. This turns out to be far from optimal for such a congested single intersection.



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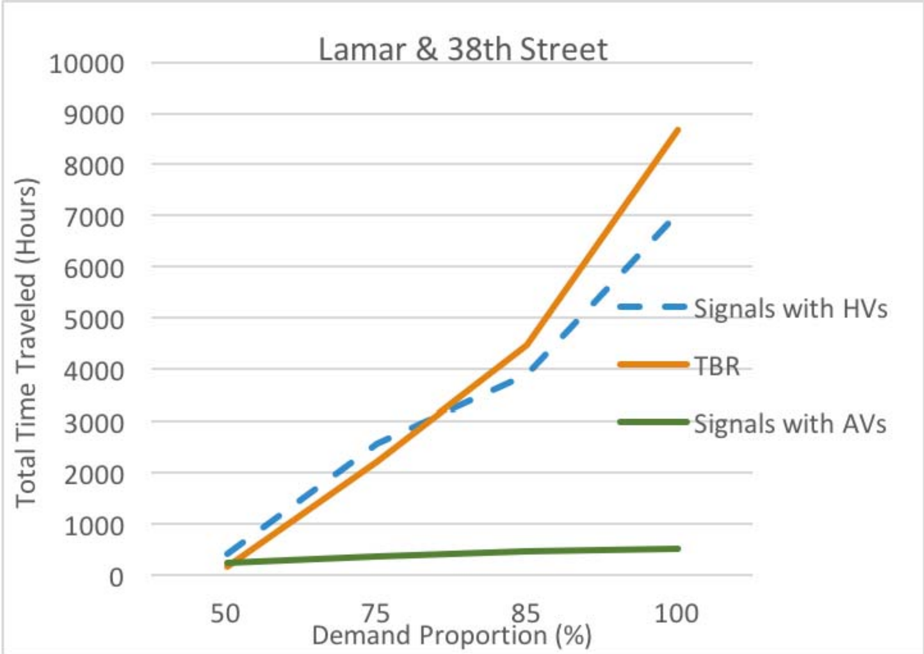

b.

Figure 1: Experimental arterial network travel time results for signals with human-operated vehicles (HVs), tile-based reservations (TBR), and signals with AVs for a) Congress Ave., and b) Lamar & 38th Street in Austin, TX

In general, TBR is less efficient with mixed flows, and results have found that TBR consistently performs worse than signals with less than 70% AV market penetration (Levin & Boyles, 2016). However, optimal TBR can always perform at least as well as optimized signals. This underscores the importance of continuing research on optimizing the intersection control strategy and introducing it at a strategic time and a specific market penetration.

Summary

- TBR may sometimes offer benefits from that of traditional traffic signals; however, there are circumstances (in the scheme as modeled) where performance is worse. Further research is needed to evaluate solutions that may be safer, more reliable, and more efficient than today's traffic signal schemes, and introduced at strategically chosen levels of CAV market penetration.

Freeways

Overall, greater capacity from CAVs' reduced reaction times improved travel times in all freeway networks tested (including I-35 through downtown Austin), with better improvements at higher demands. The level of improvement increased with AV market penetration. These results indicate that reduced following headways for CAVs are likely to improve freeway capacities. Safe use of CAV technology to reduce following headways should therefore be encouraged on freeways, as it reduces congestion without requiring investments into new road infrastructure.

In a related study outlined in the 0-6847 Final Report (Kockelman 2017) estimates were made for the impact of CAV introduction on freeway networks around Texas. These estimates are shown in Table 5.

Table 5: Estimated Impacts of CAVs on Freeway Traffic Congestion in Texas

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[1]	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%

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

Meaningful congestion reduction may be achieved even at the 10% market penetration level, with an estimated total system-wide delay reduction of nearly 6%, accounting for $760 million in economic savings. By the 90% market penetration level, more than half of freeway congestion is assumed to be eliminated, with most of the remaining congestion due to collector and arterial surface street intersections. This results in a total system-wide delay reduction of more than 38%, for a cost savings in excess of $5 billion. Of course, readers should keep in mind that these figures are meant to represent order-of-magnitude estimates of potential outcomes, and that there remains a great deal of uncertainty surrounding how these CAV systems will ultimately be implemented.

City systems

The effects of capacity improvements and TBR were studied on a model of downtown Austin. Results indicated that capacity improvements resulted in reducing congestion as CAV market penetration increased. Replacing traffic signals with TBR and FCFS policy further reduced travel times. Although the network used contains parts of the I-35, Lamar and 38th Street, and Congress Avenue subnetworks previously discussed, vehicles changed routes to avoid congestion caused by TBR, resulting in overall reductions in travel times. The average travel time for each scenario is shown in Figure 2. Contrary to results from the isolated intersection model above, benefits were realized in modeling a system of intersections rather than an isolated intersection.

While this experiment is informative for central business districts similar to Austin's, any DTA operation should be specifically performed on models of other downtowns as needed. It should be noted that the equilibrium route choice of DTA can result in increased congestion if used carelessly. Likewise, to ensure expected operation, DTA models of TBR should be carefully analyzed before implementing TBR, especially when using the FCFS policy.

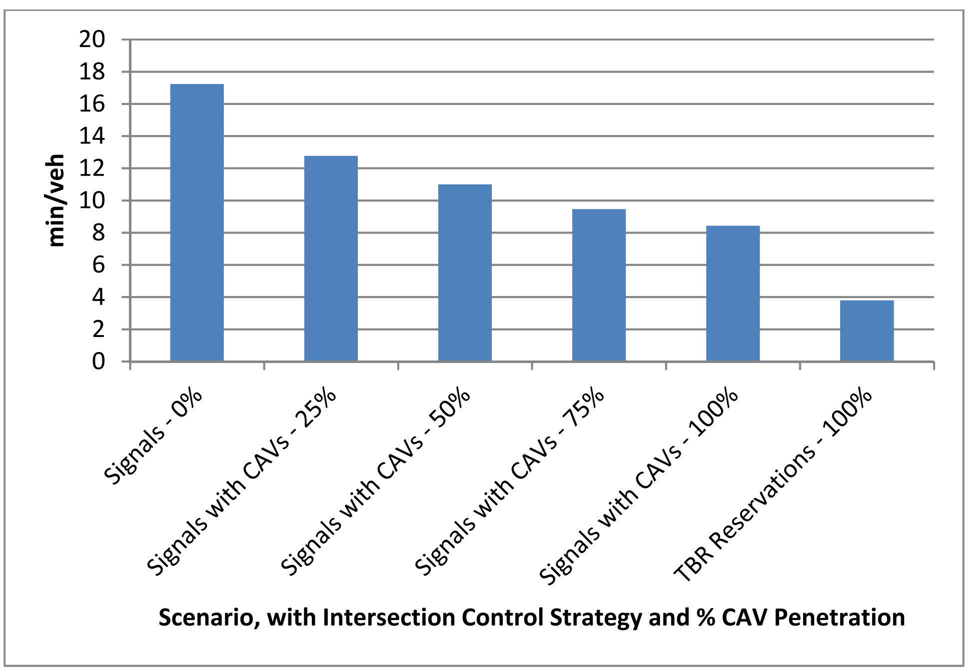

Figure 2: Travel Time per Vehicle for a Variety of Simulated Scenarios using the Downtown Austin, TX Model

Consistently in experimental results, increasing the proportion of CAVs always reduces vehicle travel because the assumed CAVs' faster reaction times (versus human drivers) reduce car-following headways, which increase lane capacities and signal-phase capacities. 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 this is true, the capacity increases described here may not materialize. Furthermore, 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.

All these simulations assume zero pedestrians and cyclists, along the routes and at the intersections. Non-instrumented, non-motorized travelers using crosswalks will disrupt intersection operations and reduce vehicle flows. <u>Both pedestrians and cyclists will probably not be able to use the tiles in TBR system unless they are aided by electronics, can be trusted to follow the guidance, and their slower speeds are accounted for.</u> Future research is needed to determine which options are the most viable and safest.

Similar approaches for choosing intersections for these experiments may be used to choose which intersections are first slated to be upgraded with "smart" technologies. While it may have made sense to choose the busiest intersections first, a more optimal and equitable solution would be to choose intersections under the criteria of maximizing the number of vehicles that are likely to pass through *at least one* smart intersection. This policy may facilitate more benefit to more vehicles with less equipment and fewer intersections.
A system-wide scheme for routing CAVs through a traffic network, such as schemes that seek dynamic user equilibrium, may reduce congestion at intersections, even if those intersections are operated as reservation-based intersections. Such schemes continue to be an active research area.

It is expected that CAVs will drastically improve safety in addition to reducing travel times. For information on crash reductions at varying market penetration levels of CAV technologies, refer to the Level 4 benefit-cost analysis section.

SAVs

SAVs are self-driving taxis, and so carry no driver costs. They can be "shared" as a rental fleet, and are likely to be quite cost competitive (as shown in Fagnant and Kockelman (2015), Chen et al. (2016), and Chen and Kockelman (2016)). Like taxis and buses, SAVs are a form of public transportation, and may be operated by public transit operators, such as a regional transit authority (e.g., Capital Metro in Austin, TX), or private entities, like Lyft and Uber. Although SAV use may be costlier than bus use, SAVs can provide on-demand, door-to-door, and lower-occupant services. SAV users will benefit from more flexible schedules and pickup/dropoff locations, shorter waiting times, greater privacy, and possibly greater comfort than buses.

Considerations

- Concerning real-time traffic routing for SAVs: Potential passengers are randomly distributed in a traffic network. The route of a shared AV should be designed and planned reasonably to maximize passengers' sharing (for example, traveling a distance as short as possible to carry passengers as many as possible), which calls for a real-time planning and design for SAVs.
- If an intersection is planned to be a reservation-based smart intersection, several safety issues must be addressed including:
    - Determining how the passengers cross the road (including whether the passengers interact with the reservation protocol, or if additional infrastructure must be built such as pedestrian bridges).
    - Understanding how to deal with emergency situations caused by passengers.
- A high SAV penetration rate will introduce the social issue of unemployment for currently paid drivers.

The experiments that produced the following results were performed on the downtown Austin network. A larger model was not used because of computational challenges and limitations.

Demand

Figure 3 shows travel time results with 28,500 to 40,000 total SAVs available. As the number of SAVs increased, waiting time decreased linearly. Both VMT and empty VMT—miles traveled while not carrying any passengers—decreased at the same rate as the number of SAVs increased. This indicates that the difference was primarily due to fewer repositioning trips to pick up the next traveler. It is intuitive that, as the number of SAVs is increased, the average distance between a waiting traveler and the closest available SAV decreases. Overall travel times in this base SAV scenario were much higher than with personal vehicles. In-vehicle travel time, interestingly, decreased for around 31,000 to 32,000 SAVs, then remained nearly constant thereafter. This may be due to a reduction in congestion when SAVs were traveling less for repositioning trips. In-vehicle travel times of 33–35 minutes, however, are double that of DTA with signals, and five times that of DTA with CAVs.

Summary

- As the number of SAVs increases, waiting time decreases. Also, VMT and empty VMT decrease. Likewise, as the number of SAVs increases, the average distance between a waiting traveler and the closest available SAV decreases.
- Overall travel times for SAVs are greater than those of personal vehicles. A contributing factor is the repositioning of empty SAVs between passengers.

Recommendation

- Realistic traffic flow modeling is valuable for assessing potential SAV performance.

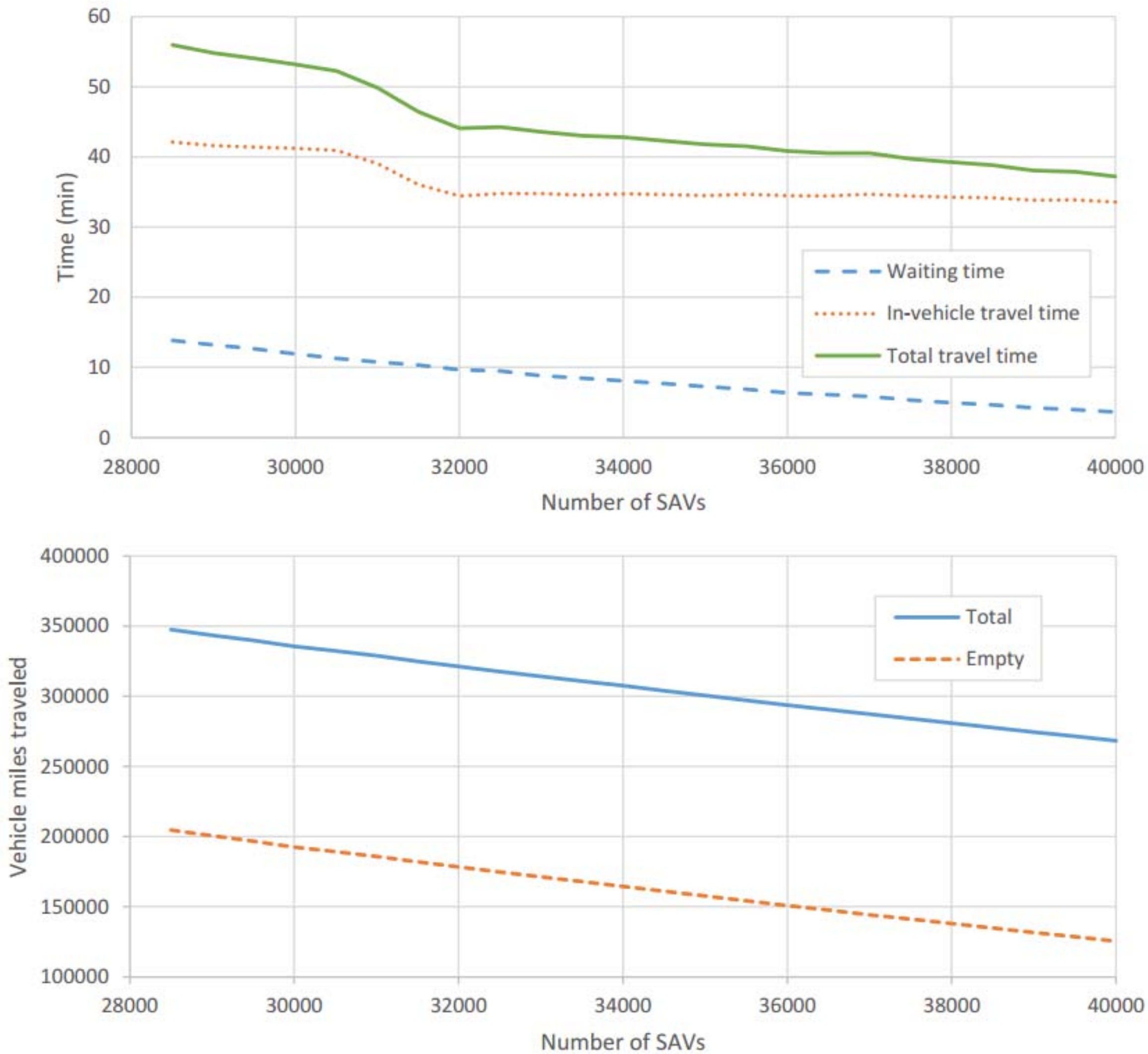

Figure 3: Travel Time and VMT for the Base SAV Scenario

Preemptive relocation

Next, the effects of preemptively relocating SAVs to match the proportion of productions of each traffic analysis zone was studied. This resulted in very high waiting times with few SAVs available. This is likely due to the fairness of assigning SAVs: travelers are prioritized by the time spent waiting. Unless a traveler was waiting at the destination of the relocating SAV, it would be re-assigned to service a different traveler, which is likely why the waiting time was so high when few SAVs were available. Although this is a reasonable policy, alternatives such as that of Fagnant and Kockelman (2014), in which travelers are prioritized according to distance from the available SAV, could improve waiting time.

As the number of SAVs increased, waiting time decreased linearly, although it was still much higher than the base scenario. One potential reason is the additional congestion resulting from relocating SAVs. This effect is illustrated by much higher empty VMT resulting from relocations. Relocating resulted in around 400,000 vehicle miles of empty travel. Empty VMT did not decrease as the number of SAVs increased, as it did in the base scenario, which likely contributed to the increasing in-vehicle travel times. The in-vehicle travel time increased linearly with the number of SAVs, which is indicative of those additional SAVs contributing significantly to congestion. In fact, beyond 20,500 SAVs, congestion prevented effective service for all travelers. Although waiting time decreased, the increases in travel time resulted in only small decreases in total travel time.

Summary

- Excessive empty driving of SAVs dramatically increases VMT, and reaches a limit that prevents effective service for all travelers.

VMT comparison

As an example of expectations concerning the introduction of CAVs and SAVs, Table 6 shows a selection of CAV and SAV scenarios in relation to the base case of only conventional autos and buses loaded on the network.

Table 6: Regional VMT Forecasts during AM Peak Period

Scenario	Parameter value assumptions				VMT per day			% Base Case	% Change relative to Scenario 1 values		
	VOTTs of CAVs & SAVs (as % of Auto)	Parking costs of CAVs as % of Auto	Operating costs of CAVs ($/mile)	Operating costs of SAVs ($/mile)	Auto	CAV	SAV		Auto	CAV	SAV
Base					5,823,350 mi	-	-				
1	50%	100%	$1/mi	$1.5/mi	1,562,157	3,926,846	1,820,202	126%			
2	25%	100%	1	1.5	803,487	5,116,016	2,298,955	141%	51.4%	130.3%	126.3%
3	75%	100%	1	1.5	2,212,197	3,149,242	1,488,724	118%	141.6%	80.2%	81.8%
4	50%	50%	1	1.5	1,561,185	3,931,598	1,817,080	126%	99.9%	100.1%	99.8%
5	50%	0%	1	1.5	1,560,335	3,937,089	1,814,158	126%	99.9%	100.3%	99.7%
6	50%	100%	1	1	1,478,870	3,805,329	2,181,801	128%	94.7%	96.9%	119.9%
7	50%	100%	1.5	1.5	1,751,416	3,660,881	2,099,617	129%	112.1%	93.2%	115.4%

In comparing this base case scenario's results (where only auto and bus modes are available to travelers) to all other scenarios, with CAV and SAV alternatives, results in over 20% more VMT, during the AM peak.

When CAVs' parking costs are assumed to be half the cost of storing regular automobiles (due to self-parking in lower-cost locations, away from the actual destination), the model predicts a roughly 4% increase in CAVs' VMT or use; when CAV parking carries zero cost, the increase is about 8%, versus the scenarios where CAV parking costs equal those of conventional automobiles. Of course, CAV self-parking does carry other costs that were not simulated: driving to a new location, parking at low or zero cost, operating costs, as well as added system VMT.

When SAV operating costs (as perceived by the users) fall to that of CAVs (about $1/mile, which is still higher than a standard automobile's assumed $0.6/mile), VMT levels by SAV are predicted to rise 20%, relative to the $1.5-per-SAV-mile scenario. However, if CAV operating costs are increased from $1/mile to $1.5/mile (to the same cost as SAVs), CAV VMT values are predicted to fall about 7%.

Summary

- The introduction of CAVs and SAVs may increase overall VMT during peak times.
- A reduction in parking cost increases CAV VMT.
- A 50% increase in CAV operating cost may reduce CAV VMT slightly. A 33% decrease in SAV operating cost may significantly increase SAV VMT.

Considerations

- Regulations may need to be addressed for scenarios in which SAV riders approve or disapprove certain tolls. Such a capability will affect the route choice of SAVs and, therefore, alter VMT and congestion.
- It may be advantageous for road configurations and dimensions to be altered to facilitate more efficient use of SAVs.

Dynamic Ride-Sharing

If people want to embrace advanced transportation technologies without increasing current traffic congestion, DOTs may consider policies facilitating dynamic ride-sharing. Dynamic ride-sharing is the ability for SAV riders to elect to pick up another rider en route who is going to a similar destination as the original rider. Most SAV scenarios resulted in greater congestion due to empty repositioning trips to reach travelers' origins. Dynamic ride-sharing was effective at reducing congestion by combining traveler trips. Interestingly, ride-sharing had the best travel times when the number of SAVs was small (4000 SAVs providing service to 62,836 travelers), and these travel times improved over personal vehicles and traffic signals, and were competitive with personal vehicles and reservation controls. More SAVs decreased waiting times, but also decreased the number of passengers per SAV and correspondingly increased congestion.

Studies predict that SAVs servicing multiple travelers incur marginally acceptable waiting times, but the travel times experienced are more similar to those of public transit. Some travelers may be unwilling to use dynamic ride-sharing if the travel times are comparably high.

Planning SAV Service

This study resulted in additional recommendations for planning for SAV service. First and foremost, models and analyses of SAVs must include realistic congestion modeling (such as the cell transmission model). Previous studies reporting outstanding benefits for SAVs assumed constant travel times, which is simply not accurate when studying tens of thousands of vehicles. Second, SAVs operated in certain modes (such as dynamic ride-sharing) could be competitive in terms of travel times with personal vehicles. Since dynamic ride-sharing reduces costs per user, it may be popular with travelers as well. Although AVs could greatly reduce transit demand, SAVs with dynamic ride-sharing may provide an effective alternative for transit agencies. SAVs could provide nearly point-to-point service at low cost, with competitive travel times, and reduce the use of personal vehicles. Cities that have considered expelling personal vehicles from their central business district should especially consider using SAVs with dynamic ride-sharing instead.

Forecasting Long-Term Adoption of CAV Technologies

Much of the analysis so far has sampled a limited set of market penetration levels. This section presents additional analysis that adds insight to the task of forecasting CAV adoption.

Technology Pricing Scenarios

Technology adoption is the percentages of households having a specific technology among the households having at least one vehicle. The pricing of technology is ever-changing and cannot be accurately predicted. The adoption of automation technology, therefore, needs to be studied at varying price reduction rates for obtaining a general idea in the long run.

A simulation forecast for the next 30 years was carried out under three price reduction scenarios. Annual price reductions of 1%, 5%, and 10% were used to execute a model that was estimated with survey data. The initial pricing of Level 1 and Level 2 technology was obtained by analyzing the packages offered by BMW, Mercedes and similar manufacturers. Connectivity, Level 3 and Level 4 technologies are a thing of the future and, therefore, experts' opinion was the sole input. However, it was assumed in the entire simulation that the WTP for additional technology and household demographics remained constant in all the subsequent years.

Table 7 shows the pricing used for the simulation and the predicted prices at a 5% reduction rate. Table 8 and Table 9 show adoption rates at 1% and 5% reduction rates, respectively.

Table 7: **Technology Prices at 5% Annual Price Reduction Rates**

Technology	201	2020	2025	2030	2035	2040	2045
Electronic Stability Control	100	77.4	59.9	46	35.8	27.7	21.5
Lane Centering	950	735.1	568.8	440.1	340.6	263.5	203.
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.
Adaptive Headlights	1,00	773.8	598.7	463.3	358.5	277.4	214.
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	450	348.2	269.4	208.5	161.3	124.8	96.6
Connectivity	200	154.8	119.7	92	71.7	55.5	42.9
Self-parking Valet	2,00	1,547.	1,197.	926.6	717.0	554.8	429.
Level 3 Automation	15,0	11,606.	8,981.	6,949.	5,377.	4,160.	3,219
Level 4 Automation	40,0	30,951.	23,949.	18,531.	14,339	11,095	8,585

Table 8: **Technology Adoption Rates at 1% Annual Price Reduction Rates**

Technology	201	2020	2025	2030	2035	2040	204
Electronic Stability Control	21.	35.4	32.2	30.1	29.0	29.2	28.5
Lane Centering	4.2	4.	2.	2.	2.	3.	4.8
Left-turn assist	4.0	8.	8.	7.	7.	7.	12.0
Cross Traffic Sensor	10.	10.3	7.	5.	5.	10.8	11.4
Adaptive Headlights	9.2	6.	3.	2.	2.	2.	2.5
Pedestrian Detection	3.3	8.	7.	7.	7.	7.	13.7
Adaptive Cruise Control	13.	13.2	9.	8.	8.	8.	11.6
Blind-spot Monitoring	9.7	14.0	11.7	11.2	10.7	10.7	15.2
Traffic Sign Recognition	2.0	3.	3.	3.	2.	3.	6.3
Emergency Automatic Braking	5.9	10.4	9.	9.	9.	9.	17.4
Connectivity	0	12.1	12.5	12.5	12.5	12.4	16.9
Self-parking Valet	0	6.	6.	5.	5.	5.	9.2
Level 3 Automation	0	2.	2.	2.	2.	2.	1.7
Level 4 Automation	0	0.	0.	1.	2.	3.	3.4

Table 9: Technology Adoption Rates at 5% Annual Price Reduction Rates

Technology	201	2020	2025	2030	2035	2040	204
Electronic Stability Control	21.	35.1	46.8	49.5	49.3	52.7	59.9
Lane Centering	4.2	4.	8.	12.8	17.9	22.7	28.6
Left-turn assist	4.0	8.	13.0	20.1	23.3	31.9	34.4
Cross Traffic Sensor	10.	13.1	17.7	19.5	30.5	32.6	42.7
Adaptive Headlights	9.2	6.	6.	9.	14.7	19.9	24.4
Pedestrian Detection	3.3	8.	15.7	24.6	28.7	37.0	39.5
Adaptive Cruise Control	13.	12.6	16.4	23.8	29.2	29.6	36.5
Blind-spot Monitoring	9.7	14.7	23.3	29.4	38.5	38.9	45.6
Traffic Sign Recognition	2.0	3.	7.	13.4	15.1	21.0	22.7
Emergency Automatic	5.9	11.4	19.9	30.3	35.5	44.5	47.3
Connectivity	0	12.2	22.1	31.0	40.0	40.8	46.9
Self-parking Valet	0	6.	12.9	17.7	23.8	23.9	27.5
Level 3 Automation	0	1.	3.	4.	6.	8.	12.6
Level 4 Automation	0	1.	3.	5.	8.	11.2	15.9

Technology Adoption

Substantial differences in technology adoption were seen between the 1% and 5% price reduction rates. This was not the case between the 5% and the 10% price reduction scenarios. (See the 0-6838-2 report [Kockelman 2016c] for the 10% reduction scenario). This result could have been due to some households' low levels of interest in such technology, whereas some households might have very strong preference for the same technology. In the 1% price reduction scenario, a few technologies were seen to be adopted less over the years. This could be due to households potentially selling vehicles with these technologies in those years.

Electronic Stability Control is predicted to remain the most preferred technology for adoption. Texans have shown most interest towards automatic braking and blind-spot monitoring technologies, with both their adoption rates being highest in 2045 at a 10% price reduction rate. Pedestrian detection was the second-least adopted technology in 2015 but is expected to be the fifth-most adopted Level 1 technology in 2045 at both 5% and 10% price reduction rates.

The adoption rates for connectivity and advanced automation technology show big jumps between 5% and 10% price reduction rates. Level 4 automation cost in 2045 would be around $8,590 and $1,700 for the two rates respectively and thus explains the jump. Also, the adoption rates for connectivity are similar to the adoption rates for Level 1 technology in 2045 for both 5% and 10% price reduction rates. Although Level 3 automation would cost around $640 in 2045, the adoption rate is only 16.9%, as most households are unwilling to pay for the technology.

Summary

- Price reduction rates of 1%, 5%, and 10% were used in specific scenarios to forecast varying technology adoption rates in the next 30 years.
- Pedestrian detection is predicted to be among the most adopted technologies in 2045 in the Level 1 cadre.
- In 2045, connectivity and Level 4 automation is forecasted to be adopted significantly high at 5% and 10% price reduction rates

Level 4 Benefit-Cost

With the emergence of CAVs, state DOTs and other transportation agencies will need new resources to manage aspects of their integration into the transportation system. In addition, DOTs will have the ability to deploy infrastructure to harness CAV capabilities. In order to properly evaluate the potential effectiveness of these strategies, it is crucial to conduct benefit/cost analysis.

As a reminder, Level 4 automation according to NHTSA is full automation of all safety-critical driving functions (no human assistance). Because full automation has not been fully realized and little data on the effects of automated driving exists, a number of assumptions based on engineering judgement were made to assess the benefits of Level 4 automation.

The potential safety benefits in the form of crash prevention are also explored in the benefit-cost analysis. It is noted that almost all crashes can be attributed to some error made by the driver. This error can be attributed to one or more of five different factors: intoxication, aggressive driving, distraction or inattention, judgement failure, and performance errors.

Table 10 shows a suite of comprehensive benefit/cost ratios, as reported in the 0-6847 Final Report using benefit estimates of mobility, safety, productivity, and leisure. A project life of 11.4 years, which is based on the average lifespan of a conventional vehicle, and discount rate of 10% were assumed and the costs used are described in the following chapter. A discount rate is a measure used to convert future costs and benefits into present value. The researchers estimated benefits at three assumed market penetration levels—10%, 50%, and 90%—to gauge the change in potential benefits as CAV adoption rises.

Table 10: Summary of Anticipated CAV Impacts across Texas

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

For a more complete reading of the methodology, please refer to the 0-6849 Final Report (Kockelman 2016b).

Safety Benefit

CAV technologies are expected to create 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 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 11 lists these pre-crash scenarios along with the corresponding crash type that typically results from each scenario.

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 11 shows each MAIS crash level along with its estimated economic cost.

Table 11: 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

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 12 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 12: 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		
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		

No.	Combination of Safety Applications	Pre-Crash Scenario	Economic Costs Saved ($1M in 2013USD)	Saved Functional-years (Years)
12	Combined Impacts of Safety Applications	Other	$2,170	32,200
	Totals		***$139,694***	***1,652,200***

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. Figure 4 shows the results of the simulations run for I-35 and Wells Branch Parkway. The number of conflicts comprehensively decreased with the addition of AVs in the traffic, from 100% human-operated vehicles to 100% AVs.

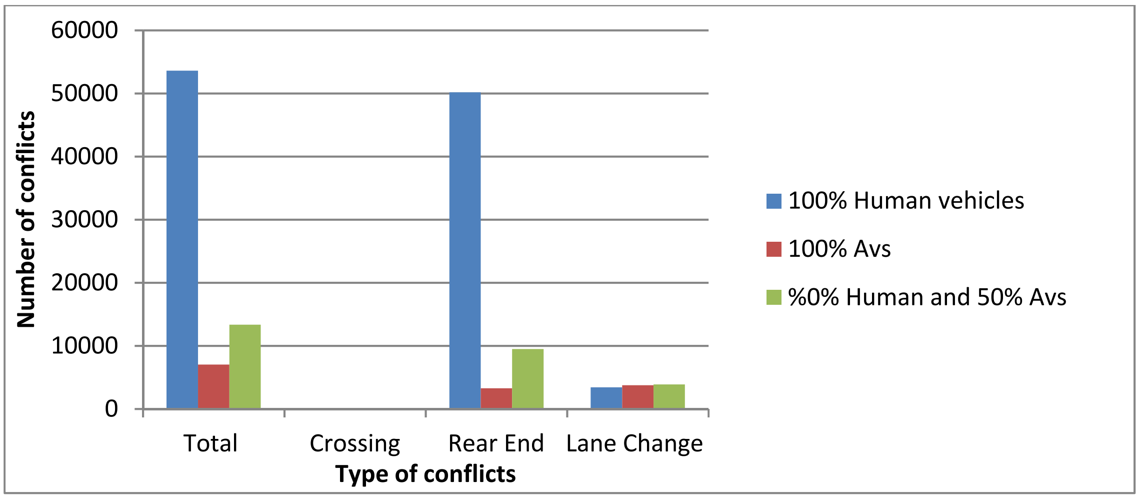

Figure 4: Intersection Conflicts Disaggregated by Type at I-35 and Wells Branch Parkway, Austin, TX.

Summary

- In the analyzed scenario, a totally automated traffic network dramatically reduces the number of conflicts in general. But, even with a 50% CAV market penetration, the conflict rate in two categories is approximately a fifth of that of a traffic network without automation.

Crash Reduction Benefit

The following crash reduction factors that were assumed for each of the five crash reduction factors are shown in Table 13. Based on the crash reduction factors assumed at the 10% CAV market penetration level, the collision rates were assumed to half at the 50% market penetration level, and halved again at the 90% market penetration level.

Table 13: Assumed Crash Reduction Factors for CAVs

Crash Factor	Types of Human Error	CAV Market Penetration		
		10%	50%	90%
Intoxication	Alcohol, drugs	99%	99.5%	99.75%
Aggressive Driving	Speeding, driving too fast for curve or conditions, erratic operation, illegal maneuver, other prohibited driver errors	90%	95%	97.5%
Distraction & Inattention	Internal and external distraction, inattention	75%	87.5%	93.8%
Judgment Failure	Failure to keep in lane, failure to yield, misjudgment of gap or other's speed, false assumption of other's action	75%	87.5%	93.8%
Performance	Inexperience, over-correction, inadequate surveillance, panic/freezing, sleep, heart attack	66.7%	83.3%	91.7%
Other Factors	All other crashes	50%	75%	87.5%

To account for the expected increase in demand resulting from CAV use, the higher levels of VMT were assumed to increase the expected number of collisions in a proportional manner from the original collision estimates. VMT increases of 3%, 12%, and 26% were assumed for the three (respective) market penetration levels in urban areas; for rural areas, 1%, 5%, and 9% VMT increases were assumed at the 10%, 50%, and 90% market penetration levels.

Summary

- Increases in CAV market penetration significantly improve safety and reduce crash experiences for those using CAVs.

Chapter 3 Implications for Modeling, Design, and Planning

This chapter addresses examples on how the introduction of CAVs influences future modeling, design, and planning activities. Travel demand models currently in use by most MPOs, DOTs, and their consultants are not set up to investigate the potential traffic impacts of CAVs and SAVs, though such vehicles are expected to be quite common over the next 20 to 30 years. Long-range city, regional, state, and national transportation planning activities should work to reflect the tremendous technological changes expected in the transportation sector, via self-driving vehicles (shared and private, passenger and freight, short-distance and long-distance). Significantly, behavioral changes precipitated by the introduction of CAVs affect emissions and air quality, crash counts, noise levels, goods delivery and product prices.

Assumptions and Scenarios

The outcomes presented in previous chapters inform assumptions that can be made concerning analysis and modeling of CAVs and SAVs at various levels of penetration. Because the future cannot be completely known at this time, a mixture of prior experimental outcomes, engineering judgement, and simplifications may all be used in future work. It also follows that it is often appropriate to use multiple scenarios, each with a selection of assumptions, to allow for sampling across a spectrum of reasonable outcomes. In proper documentation, the assumptions should be clearly identified so that interpretations of results can be properly qualified. With future work informed by earlier work, assumptions can be clarified, augmented, or replaced with real data as it becomes available.

Multiple model scenarios should be developed to illuminate a range of possible transportation system futures. These scenarios can vary the VOTTs, parking costs, headways, and other important travel choice factors. While these may be initial rough estimates, they are still useful for transportation and urban system planners and decision-makers, when charting a course for future investments and policies. The methods applied should also prove useful to travel demand modelers and planners.

Examples

As an example, Childress et al. (2015) modeled the Seattle region with the MPO's (PSRC's) existing activity-based model, and assumed CAVs can follow each other more tightly with less headway, thus increasing roadway capacity. However, CAVs also cost more to obtain, and were assumed to increase operating costs. Modelers reduced VOTT and parking costs for those choosing the CAV mode. Their scenario results indicated that improvements in roadway capacity and travel utilities will result in noticeable increases in VMT and VHT, although higher ownership and operating costs for CAVs and SAVs, respectively, somewhat counteract such trends.

Kim et al. (2015) analyzed the availability of AVs across the Atlanta, Georgia region, using the MPO's (ARC's) existing activity-based model. They assumed increases in roadway capacity, lower VOTT, lower parking costs, and 100% market penetration of the new technology (so no conventional vehicles in the mix). Their findings suggested that Atlanta travelers will make longer trips, on average, relative to the status quo or business as usual scenario (without CAV technology), due to a reduction in VOTT, resulting in increases in both VMT and VHT. However, their models predicted that annual delay per person would fall, due to higher speed travel across the network.

Chen et al. (2016) and Chen and Kockelman (2016) micro-simulated a 100 mi x 100 mi region of the Austin, Texas area, with a grid network (and fixed travel times). In some model applications, they allowed for non-SAV mode choices and used the Austin region's trip tables; they estimated strong mode splits for the SAV choice and vehicle replacement rates of about 7 to 1, even though there were many long-distance trips to serve in their simulations. Their battery-only electric vehicle simulations of these settings suggest lower replacement rates, due to long charge times and longer travel to reach a network of charging stations (vs. gasoline vehicle refueling times and gas-station locations).

It is good practice to pick a set of scenarios where a handful of samples among key input parameters are varied. In a given modeling task, separate scenarios for VOTT of 25%, 50%, and 75% from that of conventional vehicles can be used. Furthermore, CAV parking costs may be assumed to be 100%, 50%, and 0% of conventional vehicles' parking costs, because it is not known whether privately held CAVs will be allowed to travel empty to find low-cost parking. The results of different combinations of CAV and SAV operation costs can then be simulated.

To this end, Zhao and Kockelman (2017) simulated eight scenarios (using various VOTT, parking-cost, and mode-cost assumptions) across the six-county Austin region. Their results suggest 20% and higher increases in regional VMT, once SAVs and CAVs become widely available—not reflecting empty-vehicle travel on the region's roadways, or increases in motorized trip generation by those who currently must rely on transit or others to drive them. The authors note that agent-based (microsimulation) models of individuals' travel are needed, to capture dynamic ride-sharing (by strangers), vehicle sharing (SAV movements, from traveler to traveler), empty-vehicle self-parking (if permitted by roadway managers), and other behaviors. Such modeling requires new programs, more sophisticated modeling staff, and, ideally, supercomputers.

Summary

- CAVs may incur less headway, reduce VOTT, and increase overall VMT. However, there remains the possibility that such benefits will not be immediately seen because of early safety measures taken by manufacturers, traveler comfort with shorter following distances, and evolving government policy.
- With introduction of 100% CAV penetration, network speeds may increase, and annual delay per person may fall.
- It is a good practice to pick a set of scenarios where a handful of samples among key input parameters are varied.

Risk Compensation

Risk compensation is another issue to consider when systems are improved. For example, soon after cruise control was introduced, the crash rate increased because 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.

Traffic Demand Modeling

With the advent of CAVs, researchers and planners are investigating their potential travel-demand and traffic impacts, using existing travel demand modeling methods, including trip-based models and activity-based models. Unfortunately, conventional models of travel demand are not designed to accommodate self-driving or shared vehicles: essentially, vehicles become travelers in their own right. Shared vehicles also pick new destinations and routes in a very dynamic way.

To prepare for CAV availability, planning models should be modified to include the effects of CAVs on mode choice. CAVs may reduce the disutility associated with in-vehicle travel time, as well as offer new options such as empty repositioning (when allowed) to further reduce costs associated with personal vehicle travel. As mentioned earlier, this is likely to result in significant reductions in transit demand. Also, policymakers should study whether allowing empty repositioning trips makes sense, keeping in mind that complexity increases because empty repositioning trips are necessary for autonomous taxis or buses (SAVs).

It may be necessary for MPOs to take a traditional trip-based "four-step" model for an urban region, and change many key parameters and sub-model specifications to introduce new modes (private CAVs and shared AVs), with and without capacity changes, to get an initial sense of how travelers and network conditions may respond. As an example, work related to the projects that instigated this guidebook involved using data from the Austin area MPO (CAMPO), whose model covers 6 counties and currently addresses 13 trip types and purposes. The trip distribution step's gravity model was replaced with a destination choice model to accommodate the redistribution of the trips after introducing the CAVs and SAVs. This destination choice model is a multinomial logit (MNL) model. The mode choice model was also altered. For further details on the method used in this example, refer to the 0-6838-2 report, Chapter 8 (Kockelman 2016c).

As for dynamic ride-sharing, an area of interest for reducing VMT in the future, the exact impacts of dynamic ride-sharing are difficult to investigate in the regional travel demand model, particularly based on the trip-based model. The traditional travel demand model also cannot directly model the travel of AVs during empty driving.

Many aspects of the travel choice and traffic impacts remain to be examined. Most travel models track trip-makers, not vehicles. They are aggregate in space (with traffic analysis zones) and in time (with multi-hour times of day) and do not allow empty-vehicle driving, shared vehicles, or dynamic (real-time) ride-sharing. They are not designed to anticipate CAVs' impacts. Additionally, many modelers are already assuming that capacities rise notably, but such changes can only be obtained after manufacturers feel confident using their vehicles with tight headways, and passengers and traffic managers are comfortable with such operations.

As a result, agent-based simulation (as conducted in Fagnant & Kockelman 2015, Chen & Kockelman 2016, and other papers) is the best way to reflect such settings, but is much more computationally intensive than various approximate modifications to existing software packages.

Recommendation

- More advanced travel demand modeling techniques, such as activity-based and agent-based modeling, should be developed.

Emissions Modeling

Another aspect that planners must anticipate from future CAV use is the induced VMT. As mentioned earlier,CAVs are anticipated to lead to increased VMT, and those formerly unable to drive (such as those with disabilities) are able to navigate in a motorized vehicle safely. There remains the possibility of vehicles being sent around empty (to pick up the next passenger or to 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.

The modeling of emissions is highly dependent upon the guiding assumptions that are put into place within a model. These guiding assumptions are often chosen based on engineering judgement or straightforward models, and include (Wadud, 2016):

- How prevalent and influential congestion mitigation technologies are;
- How much efficient operation vehicles have, as opposed to having features that increase traditional performance;
- Whether platooning is facilitated;
- How much CAVs have penetrated the market;
- Passenger VOTT
- Total VMT
- Equitability of scheduling so as to avoid personal gain of one driver over the expense of another driver

Indeed, it has been shown in models that there can be a set of guiding assumptions that can yield a very optimistic prediction of low emissions rates. However, the guiding assumptions can also be such that an automated CAV world results in worse operation than a world with traditional vehicles. This dichotomy is referred to as the “heaven or hell outcome.” Although it is useful to look at extreme cases, it is also important to consider likely scenarios that sit well between the extremes.

Recommendation

- Run a model several times with a set of different assumptions to understand how an outcome can vary. Likewise, design with a limited set of scenarios (e.g. likely best case scenario versus likely worst case scenario) to facilitate the creation of infrastructure that is resilient to a variety of known and unknown factors. It is critical to consider the likely market condition related to the time period that is modeled, as described in earlier chapters.

Traffic Operations

The introduction of CAVs also is likely to change modeling and design of traffic operations and management. The intention of a good traffic operations and management scheme is to improve the operation of a given roadway network through the control of demand. While management strategies today may include traffic signal timing, incident response plans, dynamic message signing, and ramp metering, the management strategies of the future that concern CAVs may branch out into the connected infrastructure that influences areas such as automated route choice and advanced intersection control. Without definite standards, it is difficult to consider how these can be modeled and designed. However, parking cost and tolling would continue to be good candidates because of their applicability to both traditional vehicles and CAVs. Parking costs may vary based upon whether CAVs can find lower-cost parking lots away from their destinations. Also, SAVs would not need any paid parking.

Toll policy may also play a role in controlling the total VMT and VHT, which, in turn, may reduce traffic congestion. Increasing operating costs may also make carpooling a more attractive alternative for travelers who want to minimize their travel costs.

Suggestions

- Parking costsand tolls appear to be good traffic management tools to control overall VMT.
- Tolling schemes alternative to those that are universally mandatory or applied per-facility should be considered, such as a non-mandatory GPS-based tolling scheme that includes tax discounts for enrollment. Alternative schemes may in general affect revenue and VMT from what is expected in traditional schemes.

Chapter 4 Testing Overview

This chapter briefly describes examples of selecting and using roadways and intersections in Texas that could serve as testbeds for assessing the effectiveness of strategies related to CAV use. The examples include a limited set of scenarios concerning car and truck platooning. However, the methodologies can be extended to other types of CAV testing.

Locations must be carefully selected so that initial tests relating to CAVs are given the highest chance of showing successful results. In other words, the anticipated benefits of CAV use may not be realized if initial testbeds do not show positive results, which could motivate state agencies and other interest groups to become less interested in CAV development. Potential testbeds are identified as highway segments or intersections that can be used for testing CAV technologies. Roads or intersections can be classified into three levels of testing: preliminary, intermediate, and advanced. These stages are designated to indicate roads that could be used to test CAV platooning.

Recommendation

- As technologies begin to be introduced, one of the first that may be implemented is Level 1 safety messages. State agencies should not wait until the basic safety message scheme is mandated to start testing and implementing new solutions for CAVs.

Test Location Selection

Reducing the number of intersection-related crashes is a significant potential benefit of CAVs. New technologies that are being developed, such as Cooperative Intersection Collision Avoidance Systems (CICAS), to reduce crash frequencies at intersections. According to 2008 crash data from databases maintained by NHTSA, around 40% of the 5.8 million crashes reported that year were intersection-related (NHTSA, 2010). Indirectly related to safety, researchers have been working on developing alternative methods of intersection management that can improve throughput. This new form of intersection management-the TBR system described in Chapter 2-is intended to allow CAVs to reserve space at an intersection, which is similar in form to a slot-system. CAVs are allocated space by the automated intersection manager, which allocates space on an FCFS basis. Researchers have been working on various algorithms and simulations to test the potential of this alternative form of intersection management (Dresner & Stone, 2008; Levin & Boyles, 2015; Au et al., 2016). Improved efficiency at intersections using fully optimized TBR is expected to coincide with a reduction in intersection-related crashes.

When exploring intersections that serve as potential testbeds for testing new intersection technologies, it is infeasible to examine every intersection in the state and determine its average control delay and crash frequency. A more feasible approach is identifying general locations in Texas where intersections could most likely be used as testbeds. Since CAV use is expected to begin in urban areas, and then expand to rural areas at higher market penetration levels, the intersection testbeds should be in or near the larger cities in Texas. To provide more clarity to the geographic discussion, a TxDOT district map is employed as seen in Figure 5.

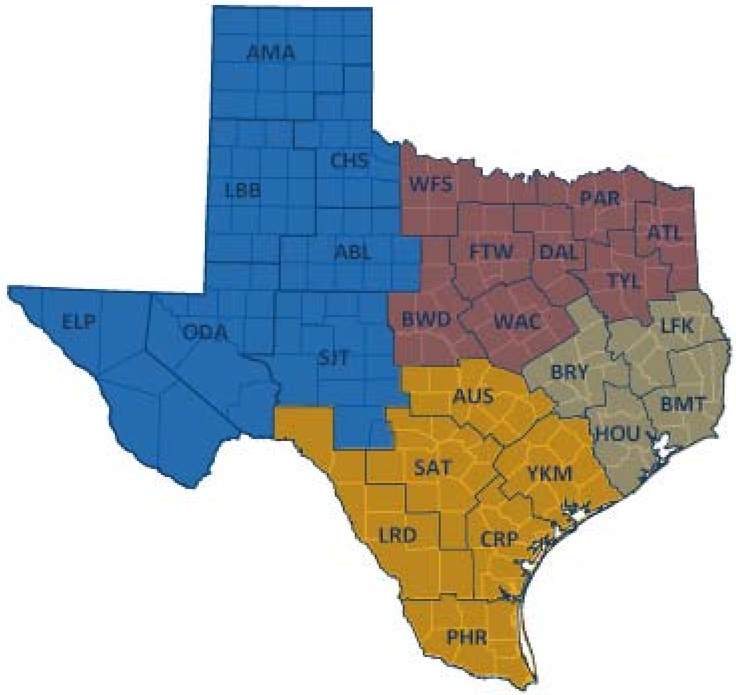

Figure 5: TxDOT District Map

Intersections that are selected for testing should be close to urban areas to best simulate traffic conditions in those highly populated areas. In order to do this, intersections testbeds should be located in the six most populated TxDOT districts: Houston (HOU), Dallas (DAL), San Antonio (SAT), Austin (AUS), Fort Worth (FTW), and El Paso (ELP). A general recommendation would be to begin initial testing on intersections in counties within these six districts that are not the respective district's most populated county. For example, if potential intersections are being looked at in the Austin District, it is reasonable to assume that lower risk and difficulty in testing would be experienced if an intersection in Williamson or Hays Counties is selected. More granular details should be incorporated into the decision process, such as intersection skew, control delay, adjacent land use, and proximity to other signals. The last factor should be taken into account when conducting tests that involve coordination between signals.

Light-Duty Vehicle Platooning

Reduced headways from CAV use will increase the capacity of roadways. However, it is important that testing of light-duty platooning is performed to help further the development of platooning technology. Potential test corridors include highway in Texas that experience significant congestion. TxDOT maintains on an annual basis a list of the 100 most congested corridors in Texas. For preliminary testing of CAV platooning, it is more feasible to not begin testing on the top congested roads in Texas where the largest benefits may be realized, but opting for corridors that will most likely prove easier to test CAV technologies. A relatively smaller testing scale will increase the probability of obtaining successful results. The list for year 2015 is compiled by the Texas A&M Transportation Institute, which uses 2014 traffic speed data for estimating delay.

It is expected that CAV use will first occur primarily in urban areas instead of rural areas. When selecting corridors for testing light-vehicle platooning, picking a group of roads that have geographic diversity within the state will help minimize any biasing of results to patterns of one urban area.

Roads shorter than five miles were not considered to ensure enough length was provided to fully observe platooning effects. Though the highest benefits will be realized from implementing CAV technologies on the roadways with higher levels of congestions, the roadways suggested for preliminary testing are expected to have a relatively higher chance of success with early and less familiar testing procedures than the roadways selected for intermediate or advanced testing, which will require more rigorous testing procedures to meet the scale.

Truck Platooning

As Texas has the second largest population of any U.S. state, trucks carry a considerable amount of people and goods throughout the state. Though platooning for light-vehicles and trucks will produce a similar type of benefit, it will be important to select roads for testing truck platooning that experience notable truck delay. When observing TTI's 2015 list of most congested roads, many roads have a significant amount of both light-duty and heavy-duty delay. But some roads contain little or no truck delay. Annual truck delay per mile ranges from a peak of just under 115,000 person-hours to less than two person-hours. A similar approach is taken for suggesting roads that can serve as testbeds for CAV truck platooning. Since many trucks carry freight over long distances, the selected roads were not limited to the six largest counties as with light-duty platooning.

Chapter 5 Summary of Recommendations

This chapter summarizes a number of key recommendations that are relevant for planning, design, and project evaluation. Many of these recommendations come from this guidebook, while others are supported in other documents. Many emerge from engineering judgement, simulations, surveys, and data analysis.

Concerning CAV Technology and Market Penetration

- Do not assume that CAV technology is a panacea. Poorly implemented technology can significantly worsen traffic system conditions.
- While reduced headways and related benefits 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.
- While CAVs may require some public investment, the benefits of CAVs may reduce the need to design and construct additional roadway capacity.
- The state should have an AV policy to encourage general adoption. A pilot program would be preferable.
- Platooning CAVs can dramatically improve capacity. Carefully consider regulation that ensures safety while reducing exposure of manufactures to undue liability. This may also apply to other CAV technologies.
- The state agency needs to proactively plan for all stages of CV/AV market penetration. This will impact the planning documents that are already required.
- The state agency will need to assist the MPOs in planning for AV/CVs. No mention of this need is found in any current manual or guidance.

Concerning Modeling, Planning, and Project Evaluation:

- Plan and design by looking at problems in terms of short-, medium-, and long-term outlooks. Build up expertise among planners, designers, operations personnel and field technicians in areas that support CAVs.
- CAVs are best supported by advanced approaches for travel demand modeling such as activity-based and agent-based modeling. New capabilities for using and refining these models should be developed.
- Because of unknowns concerning CAVs, it is most appropriate to establish and analyze multiple scenarios that cover a spectrum of feasible parameters that are expected at particular future timeframes.
- The reduction of following headway between vehicles generally reduces congestion. The use of these technologies should be encouraged when safe. Other modeling parameters that are subject to change with CAV introduction are a reduction in VOTT, and increase in VMT.

- The allowing of empty driving, or the operation of CAVs or SAVs with no passengers, leads to a significant increase in VMT and congestion, with the possibility of nullifying or worsening traffic systems from that of traditional vehicles. Empty driving should therefore be strongly limited, with an empty-VMT cap of 10 to 15%.
- In traffic operations, parking costs and tolls appear to be good traffic management tools to control overall VMT, both for traditional vehicles and CAVs.
- Incorporate an improved sense of infrastructure reliability into planning and project evaluation.
- Continue conducting research as technologies mature.

The following practice lists contain additional, specific recommendations to governing agencies in preparing for CAV and SAV adoption. These are also found in the TxDOT Project 0-6849 Guidebook (Kockelman 2016a).

Recommendations for Short-Term Practices

1) Any large transportation agency 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.

Recommendations for 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.

Recommendations for 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.

Acknowledgements

The authors thank Mr. Scott Schauer-West, Ms. Maureen Kelly, and Mrs. Amy Banker for their constructive comments and editing.

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