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Transportation Planning Implications of Automated/Connected Vehicles on Texas Highways

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TEXAS A&M TRANSPORTATION INSTITUTE
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16. Abstract
This research project was focused on the transportation planning implications of automated/connected vehicles (AV/CVs) on Texas highways. The research assessed how these potentially transformative technologies can be included in transportation planning to assist the decision-making process. Researchers completed seven tasks for the project. First, the research team briefly defined existing AV/CV technologies and explored future technologies by conducting a literature review and drawing upon previous research. Next, the research team examined potential changes that AV/CVs may have on travel behavior, urban form, and other aspects of the transportation system. The research team also studied the potential effects of automation on commercial vehicle transportation and freight. The research study analyzed how travel modeling could be affected by AV/CVs and conducted some experimental model runs using a trip-based model from the Austin, Texas, region. The project also included a statewide web-based behavioral preferences survey and a series of three stakeholder workshops held in spring 2016. Based on the study findings, this report presents the potential changes to the transportation planning process needed to address AV/CV technology and inform the decision-making process, despite the many uncertainties about how AV/CVs will impact the transportation system.

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

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CHAPTER 1. INTRODUCTION

Automated vehicle (AV) and connected vehicle (CV) technologies are potentially transformative technologies with impacts, costs, and benefits to the transportation system that are highly uncertain. Automated and connected vehicles are both advanced vehicle technologies, poised to allow for major changes to take place in the transportation system and provide many benefits. Greater mobility, fewer crashes, and a cleaner environment are all possible through these technologies. However, their potential is not yet fully realized.

AV technology takes some or all of the responsibility of driving out of the hands of a human driver and operates by gathering data about the world around the vehicle. Future capabilities include autonomy (robotics) where vehicles can also make decisions, such as for navigation, without human input. AVs rely on technologies such as light detection and ranging (LIDAR), radar, global positioning system (GPS), and high-definition maps to understand the world. AVs are not yet fully developed but are rapidly maturing. The available vehicle technologies are limited to occasional intervention in the driving task. AVs currently in development will assume a much larger share of the driving task, and original equipment manufacturers (OEMs) are working on vehicles that would never need a driver to intervene. The expected development path is uncertain, but it is clear that automation is going to be a driving force in transportation systems of the 21st century.

CV technology functions by allowing vehicles (and buses, pedestrians, and other modes of transportation) to send and receive information between each other. Applications developed based on information-sharing enable vehicles, pedestrians, cyclists, and other road users to know about critical situations on the road ahead. Not only does this information exchange improve safety, it also could improve mobility, reduce the environmental impacts of transportation, and make the overall transportation system more efficient. CVs require several pieces of hardware and are enabled by software applications. A CV does not directly intervene in the transportation environment; instead, it gives information to entities involved and enables those entities to act on the information. This is an important distinction with automation; AVs automate some or all of the driving task, while CVs provide information to the automated systems in each vehicle to assist drivers, pedestrians, and other vehicles in the transportation environment.

How these two technologies will converge is unclear. If they do cooperate, there are opportunities for additive benefits that each technology cannot provide in isolation. Barriers to such convergence such as legal and liability concerns remain unresolved at this time.

Ultimately, convergence of many technologies is expected, linking together AV/CV with personal communications and web-enabled devices throughout homes and businesses. This convergence is also expected to have a significant impact on the array of mobility options that people have to choose from and stimulate the invention and growth of various multimodal solutions that are available to the traveling public.

To better understand the current and future impacts of AVs and CVs, Texas A&M Transportation Institute (TTI) researchers conducted a study on the transportation planning implications of automated vehicles on Texas highways. This report presents the details related to six tasks completed as part of the study:

- Task 1: Examine the state of AV/CV technology and its current development direction.
- Task 2: Assess the potential impacts of AV/CV technology on personal travel.
- Task 3: Examine the potential transportation impacts of automated/connected vehicles on commercial and freight transportation.
- Task 4: Examine the potential automated/connected vehicle impacts on Texas travel forecasting.
- Task 5: Conduct a web-based behavioral survey to explore the potential acceptance and impact of automated vehicle technology.
- Task 6: Conduct stakeholder workshops.
- Task 7: Evaluate the Impacts to the Transportation Planning Process from Automated/Connected Vehicles

Chapters 2–7 of this report detail the above tasks, respectively. Chapter 8 concludes the report with a discussion of the potential impacts of AV/CVs to the transportation planning process based on the findings of this study.

CHAPTER 2. CURRENT AND FUTURE STATE OF AUTOMATED/CONNECTED VEHICLE TECHNOLOGY

INTRODUCTION

This chapter presents the current state of development and implementation for automated and connected vehicle technology, laying the groundwork to review the potential changes that AV/CV technology may have with respect to travel behavior, urban form, and other aspects of the transportation system.

In addition to describing the state of AV/CV technologies, this chapter also discusses the expected path of development of AV/CV technologies and foreseeable issues that need to be resolved. An appendix of terminology (Appendix A) is provided as a reference to ensure consistency in discussions of AV/CV capabilities and implications. Moreover, a literature review (Appendix B) of existing research and analysis on AV/CV technologies and their impacts is included.

AUTOMATED VEHICLE TECHNOLOGIES

Overview

An **automated vehicle** is a vehicle that either wholly or partly controls the driving task, independent of direct driver input. This technology is driven by advancements in computer and automotive technologies that enable vehicle systems to control braking, steering, throttle, or motive power. An AV is expected to operate in a manner similar to a human driver, meeting expectations to obey traffic rules, monitor the environment, be aware of proximate vehicles and pedestrians, anticipate the actions of neighboring vehicles, and take actions to avoid potential hazards or collisions (*1*).

Automated features range from available options such as adaptive cruise control and park assistance, which assist drivers with particular aspects of the driving task, to complex systems that in combination allow a vehicle to navigate and operate without human involvement. Self-driving vehicles that operate without driver participation are currently being tested, although they are not publically available. Some industry predictions claim these could be available within the next 10 years, but the adoption of highly automated vehicles is dependent on many social, economic, environmental, political, and technological factors (*2*).

Crash prevention and safety benefits have been the primary drivers of AV technology development. The majority of currently available AV technologies are designed to assist a driver with the driving task for safety improvement. However, as other potential benefits of the technology are investigated, additional goals may influence market demand in the future. For instance, on its official blog, Google states that its automated car technology may "help prevent traffic accidents, free up people's time and reduce carbon emissions by fundamentally changing car use" (*3*). Other benefits include time savings, stress reduction, greater modal choice (lifestyle), access to new technology, and others. As the technology advances, these ancillary benefits may grow and new impacts and challenges may emerge. Challenges may arise as well as transportation infrastructure that has historically been designed to meet human characteristics is reimagined to meet the needs of computers and machine learning.

Taxonomy and Classification

AVs are typically defined by their degree of automation. They are classified into a series of levels that reflect a vehicle's capabilities on a scale from no automation to full automation. Governmental and industry groups have developed standardized terminology and classification systems that provide a consistent and clearly defined lexicon for the discussion of AV technologies.

The terms autonomous vehicle and self-driving vehicle are often used to describe AVs, but these terms can be misleading if used incorrectly. A fully automated self-driving vehicle, capable of controlling all aspects of vehicle operation, would be considered an AV at a particular, and advanced, point along the spectrum in most, if not all, classifications. The term autonomous implies a completely self-operating or self-governing vehicle, a characterization that only applies to a small number of AVs undergoing research and development. In contrast, the term automated vehicle, which will be used throughout this research, refers to the application of computer or mechanized systems that allow a vehicle to control all or part of the driving task.

Appendix A defines terms commonly used in reference to automated and connected vehicle technology.

NHTSA Policy on Vehicle Automation

A widely accepted standard for AV classification is defined by the National Highway Transportation Safety Administration (NHTSA). NHTSA is a federal agency established to undertake safety programs including traffic safety research and the enforcement of safety performance standards. The NHTSA classification includes five levels, ranging from no automation (Level 0) to full automation (Level 4). This classification was released along with policy recommendations on automated vehicle testing and regulation in 2013. NHTSA defines AVs using the classifications described in Table 1 (*4*).

Table 1. NHTSA Levels of Automation (*4*).

Level	Definition	Description
Level 0	No Automation	The driver is in complete and sole control of the primary vehicle controls—brake, steering, throttle, and motive power—at all times. The vehicle may include automated warning systems to alert drivers to danger.
Level 1	Function-Specific Automation	Automation at this level involves one or more specific control functions, although if multiple automated components exist, they operate independent of each other. Examples include electronic stability control or pre-charged brakes, where the vehicle automatically assists with braking to enable the driver to regain control of the vehicle or stop faster than possible by acting alone.
Level 2	Combined Function Automation	This level involves automation of at least two primary control functions, which work in unison to relieve the driver of control of these aspects of the driving task. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centering.
Level 3	Limited Self-Driving Automation	Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and, in those conditions, to rely heavily on the vehicle to monitor for changes requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The Google car is an example of limited self-driving automation.
Level 4	Full Self-Driving Automation	The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.

SAE International's AV Standard

In 2014, the Society of Automotive Engineers (SAE) developed another classification for automated vehicles in standard J3016: *Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems* (*5*). SAE International, a global association of aerospace, automotive, and commercial vehicle industry engineers and experts, offers an industry perspective on vehicle automation (*6*). The SAE classification includes six levels, ranging from no automation (Level 0) to full automation (Level 5). The levels are defined by the respective role of the human driver or the automated driving system in four aspects of the driving task—steering and acceleration, monitoring of the environment, fallback responsibility for the driving task, and driving mode. The hierarchy includes a critical distinction between Level 2 and Level

3, at which point the automated driving system monitors the driving environment instead of the human driver. At Level 3, a driver is still expected to be ready and able to take over control of the vehicle if necessary. SAE's classification system is described in detail in Figure 1.

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 1. Definitions of SAE Classification Levels (J3016) (*5*).

SAE defines some additional terminology that is used in its classification scheme (*5*):

- **Dynamic driving task** includes the *operational* (steering, braking, accelerating, monitoring the vehicle and roadway) and *tactical* (responding to events, determining when to change lanes, turn, use signals, etc.) aspects of the driving task, but not the *strategic* (determining destinations and waypoints) aspect of the driving task.
- **Driving mode** is a type of driving scenario with characteristic dynamic driving task requirements (e.g., expressway merging, high-speed cruising, low-speed traffic jam, closed-campus operations).
- **Request to intervene** is notification by the automated driving system to a human driver that he or she should promptly begin or resume performance of the dynamic driving task.

Use of Classifications

The NHTSA and SAE standards both provide useful information to describe and distinguish among AVs. However, the NHTSA levels will be the standard referred to in this report for several reasons. As a U.S. governmental agency, NHTSA participates in research on vehicle automation; provides policy guidance for states considering testing, licensing, and regulation of AVs; and enforces standards for vehicle safety (*4*). The NHTSA classification is a widely understood taxonomy for discussing AV technology among researchers, government officials, and industry representatives. The NHTSA classification is a useful guideline for communicating about AV technology with consistency and may be useful in conjunction with other classifications.

AV Technology

AVs rely on automotive and computer technologies that allow the vehicle to respond to the driving environment. Typically, a variety of sensors allow an AV to detect and interpret the surrounding environment. Information is transferred to computer systems that receive, interpret, and send orders to electronic vehicle controls. This process enables the AV to control the basic functions of vehicle operation—acceleration, braking, and steering—in a dynamic driving environment.

For an AV to achieve the expectation of driving itself, it has to equal or surpass the abilities of a human driver. Researchers at the Center for Urban Transportation Research in Florida describe a simplified four-step loop that illustrates the tasks that an AV would have to execute to operate a vehicle. The steps are:

1. Sense the environment (what is in my vicinity?).
2. Decipher its own location (where am I on a global map?).
3. Plan its next move (what should I do next?).
4. Execute the plan (*1*).

Various technologies and hardware allow a vehicle to perceive and understand its surroundings and exhibit vehicle control. Table 2 summarizes the technologies that contribute to vehicle automation and some of the current limitations and opportunities of those technologies.

Table 2. Common AV Technologies (*7, 8*).

Technology	Definition	Limitations and Opportunities
Radar	A system using radio waves for range and object detection.	Mature technology and relatively inexpensive.
Computer Imaging	A process by which computers interpret images to better understand their elements, including road striping, stop signs, and traffic signals.	Variation across driving environments can be challenging to identify and interpret.
Ultrasonic Sensors	Like radar, ultrasonic sensors are used in range and object detection.	Better accuracy than radar in short-range situations.
LIDAR	A portmanteau of light and radar, LIDAR technology was developed in the 1960s to use the ability of radar to calculate distance and a laser's "focused imaging capabilities." It is an optical remote sensing technology that measures distance to a target or other properties of the target by illuminating it with light.	LIDAR systems enable 360° viewing but are still very expensive. There can be issues with noise removal, interpolation to fixed-point spacings, and triangulation.
GPS	GPS is a space-based satellite navigation system that provides location and time information anywhere on or near earth.	The accuracy of a GPS receiver is about ±10 m, which is not practical for locating an object the size of an automobile, which is about 3-m long.
Differential Global Positioning System (DGPS)	DGPS is an enhancement to GPS that improves location accuracy from ±10 m to about 10 cm.	The DGPS correction signal loses approximately 1 m of accuracy for every 150 km. Shadowing from buildings, underpasses, and foliage causes temporary losses of signal.
Real-Time Kinematic Satellite Navigation	Navigation based on the use of carrier phase measurements of GPS, Global Navigation Satellite System, and/or Galileo signals where a single reference station provides the real-time corrections.	The base station rebroadcasts the phase of the carrier that it measured; the mobile units compare their own phase measurements with the ones received from the base station.
Digital Mapping	The process by which a collection of data is compiled and formatted into a virtual image.	Only some parts of the world have been mapped (mainly urban areas), and there is a need for a critical mass of mappers to enter and cross-validate data in order to achieve a satisfactory degree of accuracy and currency.

The availability and development of each of these technologies varies. This variation can be compared using a framework that considers four factors: cost, reliability, maturity, and regulatory dependence (*7*).

Applications of AV Technology

AVs use these technologies to take responsibility for some or all of the tasks involved in driving and operating a vehicle. The automated functions of AVs vary in purpose and use different combinations of technologies to achieve these purposes. Many are designed to alert the driver to potential hazards though visual, auditory, or haptic (related to touch) signals. Warning-only systems are giving way to autonomous control systems, often called advanced driver assistance systems, that control some driving task. Features are often triggered in specific driving situations, such as to assist with parallel parking or to avoid an impending collision. AVs with high-level automation are expected to allow motorists enough freedom from the driving tasks that they can indulge in other activities, such as sleep or work, while in transit.

AVs equipped with single-function applications, consistent with NHTSA's Level 1 automation, are commercially available. These functions typically provide collision avoidance and safety benefits, while the human driver is still responsible for the driving task. In some existing vehicles, two functions may be combined in a way that meets the definition of Level 2 automation. In both Level 1 and Level 2 AVs, the driver is still heavily involved in vehicle operation and decision making.

Higher-level AVs, including vehicles that successfully navigate urban environments without driver involvement, are being tested by private companies. Google, a software company, has logged nearly 1 million miles of travel with vehicles retrofitted with AV technology on the streets near its Mountain View, California, headquarters. The company recently announced it will be testing fully self-driving AV prototypes, like the one shown in Figure 2 (*9*).

Figure 2. Google's AV Prototype, On-Street Testing (*9*).

Several automated functions, many of which are available on new vehicle models, are discussed briefly below. AVs use the capabilities of radar, computer imaging, LIDAR, and others to enable automated functions and features that contribute to the driving task.

Antilock brakes. Antilock brakes prevent wheels from locking up and skidding when a driver brakes, particularly on wet or slippery roadway surfaces. This early automation feature automatically pulses the brake pressure on the wheels to prevent skidding.

Blind-spot information systems. Sensors monitor the side of a vehicle for other vehicles approaching blind spots and transmit an alert to the driver. Typically, a visual alert appears on or near the side mirrors if a vehicle is detected. Some systems may activate the brake or steering controls to keep the vehicle in its lane (*10*).

Electronic stability control (ESC). ESC is a system that uses automatic computer-controlled braking to prevent loss of control if a vehicle loses directional stability or control during a skid. This loss of control is a leading cause of run-off-the-road crashes and rollovers. NHTSA ruled to require the installation of ESC on all light-duty passenger vehicles starting by model year 2012. ESC is estimated to reduce single-vehicle crashes by 34 percent for passenger cars and 59 percent for SUVs (*11*).

Park assist. Cameras and sensors detect rear objects and available space when a vehicle is backing up, reducing the difficulty of parallel parking or in some cases enabling the vehicle to nearly park itself. Often, a rearview camera is displayed on the vehicle dashboard to assist a driver with the parking or backing-up task. The specifications can vary as manufacturers use different combinations of sensors (such as radar, ultrasonic imaging, or computer imaging) for this feature. In addition, some automated parking systems, called advanced park assist, are built upon infrastructure-based laser sensors and Wi-Fi. These systems allow a vehicle to navigate into a parking garage, park itself in an available spot, and later return to the vehicle owner. This level of park assist is not commercially available today (*8*).

Adaptive cruise control (ACC). Similar to regular cruise control, ACC allows the driver to set a desired speed that the vehicle maintains automatically. ACC uses sensors to track the distance from the vehicle ahead and maintains a safe gap by accelerating or braking to adjust to changes in traffic speed. While it can be related to front crash prevention, this feature is typically marketed as a convenience rather than a safety measure (*10*). Another emerging technology is cooperative adaptive cruise control (CACC), which uses communication between vehicles to see beyond just the next vehicle to anticipate and respond to changes in traffic flow faster and with more precision (*12*).

Collision prevention systems. Several automotive manufacturers offer a suite of functions that detect, warn, and/or respond to potential collisions.

Forward collision prevention. Automated systems can provide forward collision warning or forward collision avoidance. Collision warning systems alert a driver if the vehicle is accelerating at a rate at which it would be likely to crash into a vehicle ahead. The system may use cameras, radar, or LIDAR to detect a vehicle ahead, and some systems can recognize pedestrians as well. Combined with autonomous braking, a vehicle can offer forward collision avoidance where the vehicle will brake on its own if the driver does not respond in time. Several OEMs currently offer forward collision warning with and without the automatic brake function (*10*).

Lane departure warning (LDW). LDW is a system using cameras to track vehicle position relative to a driving lane in order to provide feedback and/or steering assistance to help maintain the vehicle position in the lane. Although LDW is a relatively new technology, early field operational tests have shown the technology to be effective in reducing the number of relevant crashes.

Prevalence of Automated Features

Among available models, only driver warnings (Level 0) and single-function features (Level 1) exist today. More advanced functions, such as advanced park assist and CACC, are under development.

Hundreds of current vehicle models are available with one or more automated features. Most of the existing features are intended and marketed for their safety and collision avoidance potential. The proliferation of a selection of these features, based on data reported by the Highway Loss Data Institute in 2013, is summarized in Table 3 (*13*).

Table 3. Prevalence of Collision Avoidance Technologies (*13*).

Collision Avoidance Technology	**# of Models in 2013**
Adaptive headlights	250
Blind-spot information systems	244
Forward collision warning	211
Lane departure warning	146
Autonomous emergency braking	107

A study by the Insurance Institute for Highway Safety suggests that the combination of side view assist, forward collision warning/mitigation, lane departure warning/prevention, and adaptive headlights on all vehicles might prevent or mitigate up to 1,866,000 crashes each year including 10,238 fatal crashes (*10*).

NHTSA supports the application of crash avoidance technologies that have demonstrated the highest potential for crash avoidance safety benefits. Electronic stability control, lane departure avoidance, and rear-end collision avoidance were identified as priority technologies in NHTSA's New Car Assessment Program in 2007. Furthermore, electronic stability control is now required on all new vehicles since model year 2012. Because they are still limited in overall market penetration, it is difficult to determine the effectiveness of these new technologies without more significant real-world evaluation.

Expected Development Path

As AV technology develops, there is a great deal of uncertainty around the deployment and potential proliferation of automated vehicles. Level 1 and Level 2 AVs equipped with safety and other features are commercially available but exist on the roadways in low numbers. Higher-level AVs, including fully self-driving vehicles, are being developed and tested by many automotive manufacturers and some other corporations, such as Google. The costs and benefits of AVs are uncertain, and the level and pace of market penetration will become more clear only as more testing occurs. In addition to technological advancements, AV development will depend on the financial costs of various components and external factors such as regulation, insurance, and market demand.

AV technology is developing rapidly, but many of its applications have had limited or no real-world experience. A report from the Center for Urban Transportation Research identified several technological barriers to the deployment of automated vehicles in urban environments based on current AV technology. These barriers include:

- Limited ability to properly fuse multiple sensor data streams.
- Difficulty in handling a highly dynamic environment.
- Limited and unreliable GPS information.
- Sensor susceptibility to noise in the environment.
- Unreliable electronic components.
- Difficulties in negotiating with human drivers.
- Inability to guarantee robust handling of uncertain environments or surprise events.
- Inability to handle harsh driving conditions (*1*).

Level 1 and Level 2 vehicle automation are currently available on some vehicle models, and more are expected to enter the market in the near future. Individual functions and features exhibit different timelines as well.

A 2014 industry analysis summarized the current or projected availability of various AV functions (*2*). These functions are presented in Figure 3. While features such as automated cruise control, automated lane-keeping, and automated braking assistance are already available, other technologies are still in development and will likely phase in over time.

Functions to be automated

Function	Autonomy needed	Availability
Following	Speed control: Fixed □ Variable	ACC: 1995
Stay in lane	Steering within lane	LKA: 2001
Object detection	Detect pedestrian & other objects	PDS: 2010
Read signs	Spot, sense & recognize signs	TSR: 2008
Braking	Sense & recognize when to brake	Multiple systems: 2003
Switch lane	Steering to another lane	Expected 2016
Know position	Always sense accurate position	Expected by 2018
Navigate	Determine driving routes	Expected by 2018
Obey traffic laws	Drive according to traffic laws	Expected by 2018
AP: Traffic Jam	Follow traffic flow at all speeds	TJA: 2013
AP: Highway	Drive, pass at highway speeds	Expected by 2017
AP: Parking	Find parking, park & retrieve	Expected by 2018
Self-driving	All driving functions; Plus driver mode	Expected by 2025
Self-driving only	All driving functions; No driver mode	Expected before 2030

Source: IHS © 2014 IHS

Figure 3. Availability of AV Functions (*2*).

Non-technological factors will impact the development, deployment, and market penetration of AVs. These factors include governmental actions, regulations, legal and liability issues, privacy and security needs or challenges, personal preferences, and infrastructure implementation. Environmental, economic, and social factors that affect transportation demand and costs must be considered in an evaluation of AVs as well (*14*).

Policy and regulatory actions regarding AV technology will likely influence deployment. Automated features such as electronic stability control are required on all new vehicles. NHTSA's AV policy statement includes formal recommendations for states considering high-level AV operation, with a focus on testing and licensing. NHTSA states that any future regulation "must appropriately balance the need to ensure motor vehicle safety with the flexibility to innovate" (*4*). While several states have passed legislation to regulate or oversee AVs, some legal analyses have suggested that AVs are probably legal under the existing regulations in most states (*15*).

The influence of AVs on travel behavior is another factor that could have dramatic effects on deployment scenarios. AV availability could allow motorists to engage in other activities while in transit, increasing productivity and decreasing the costs of longer commutes. In contrast, AVs may lower the cost of taxi travel or facilitate new forms of shared, public transportation that decrease the need for vehicle ownership.

Government agencies, automotive manufacturers, and other companies have made clear that they are pursuing AV technology with expectations of broad consumer appeal. However, there are few robust analyses that project market penetration for AVs over time. The existing projections vary widely, in both the figures projected and the formulation of those projections. In order to compare various projections, the results of three projections were normalized by converting the results of the analyses into penetration as both a percent of the overall vehicle fleet and the actual number of vehicles (*2*, *16*, *17*). Table 4 shows a comparison of three projections. The projections vary significantly, but all suggest some degree of AV penetration by 2025 and as much as 15 percent in 2035.

Table 4. AV Market Penetration Comparison.

	VTPI		IHS Automotive		Navigant	
Year	**Vehicles Sold**	**Market Penetration**	**Vehicles Sold**	**Market Penetration**	**Vehicles Sold**	**Market Penetration**
2015					0	0.00%
2020					0	0.00%
2025	4,665,112	1.50%	100,000	0.03%	500,000	0.16%
2026			350,000	0.11%		
2027			850,000	0.27%		
2028			1,500,000	0.47%		
2029			2,550,000	0.79%		
2030			3,900,000	1.20%	10,000,000	3.09%
2031			5,650,000	1.73%		
2032			7,850,000	2.39%		
2033			10,400,000	3.15%		
2034			13,400,000	4.04%		
2035	49,901,568	15%	16,900,000	5.06%	17,000,000	5.09%
2045	105,482,277	30%				
2055	185,055,730	50%				

Google predicted in 2012 that the Google car would be publically available in five years (*18*). General Motors predicts self-driving vehicles may be available within a decade (*19*). IHS Automotive suggests higher-level (Level 3) AVs will incrementally phase in through different driving scenarios, starting with a traffic jam mode. This would be followed by highway mode and parking modes by 2020 (*2*).

Table 5 presents a range of deployment scenarios based on the NHTSA AV levels. Level 3 self-driving vehicles may be available as early as three years away, while Level 4 AVs may emerge in seven years.

Table 5. Projections of NHTSA Level Automation (*8*).

NHTSA Automation Level	Forecasted Range
1—Function-Specific	Now
2—Combined Function	Now to 3 years away
3—Limited Self-Driving	3 to 10+ years away
4—Full Self-Driving	7 to 12+ years away

Of course, the deployment of AVs will be influenced by a range of factors, making projections of availability and market penetration highly speculative. Forecasts should be updated as more information becomes available.

CONNECTED VEHICLE TECHNOLOGIES

Overview

CV technology, as used in this report, refers to a discrete set of technologies that enable vehicles, roadway infrastructure, and various modes of transportation to transmit information between each other. This information exchange platform facilitates applications that can help road users accomplish a variety of goals: decreasing crashes and increasing safety, reducing the environmental impacts of driving, and improving mobility for road users. The applications help users make better choices by giving road users relevant and timely information, like warning a motorist that a crash may be about to occur, suggesting how to enter and leave an intersection to maximize fuel economy and reduce emissions, or informing a motorist how a change of driving behavior in a congested area could harmonize and improve traffic flow. Taken in totality, this communications platform and its associated applications represent the CV system. A CV is a vehicle equipped with the capabilities to participate in this environment. CVs are the result of more than a decade of research and development, and are rapidly approaching deployment in the United States.

The U.S. Department of Transportation (USDOT) and NHTSA spearheaded a CV research program over the previous decade. The program primarily focuses on decreasing crashes by providing information in the form of warnings or alerts to drivers about safety-critical issues in their environment. One application (known as spot weather impact warning) alerts drivers to unsafe weather conditions (e.g., flooding, ice, or fog) on the road ahead (*20*). The application would prevent crashes by warning a driver about a hazard with sufficient advanced notice to enable the driver to take corrective action.

Taxonomy and Classification

Communications between different elements in the CV system have come to be known by a number of acronyms, as shown in Table 6.

Table 6. Common Connected Vehicle Acronyms and Definitions.

Acronym	Definition
V2V	Vehicle-to-vehicle: vehicles communicating with each other
V2I	Vehicle-to-infrastructure: vehicles communicating with the infrastructure
V2P	Vehicle-to-pedestrian: vehicles communicating with pedestrians
V2X	Vehicle-to-other: vehicles communicating with other modes of transportation or other entities

CV Technology

Hardware

CVs primarily function by sending and receiving information through a wireless transmission protocol known as dedicated short-range communications (DSRC). DSRC devices are installed in vehicles, on roadside infrastructure, and in other modes of transportation, and they transmit a set of information known as a basic safety message (BSM).

The information is transmitted through both in-vehicle devices and infrastructure-based devices. In-vehicle devices are referred to as onboard equipment or devices, which include both equipment that the OEM installs during the vehicle's manufacturing (known as an OEM device) and aftermarket devices that are installed after the vehicle is sold (*21*).

When the infrastructure needs to communicate with vehicles, devices known as roadside equipment (RSE) or roadside units (RSUs) are used. Not only do these RSUs communicate with vehicles, they also allow vehicles to update their security certificates.

For V2V communication to occur, two sets of devices are needed: devices that enable vehicles to generate and send a BSM, and devices that enable vehicles to receive and interpret a BSM (see Figure 4). When generating messages, a vehicle's computer combines location information (gathered through GPS) with other information gathered from the vehicle's existing equipment (e.g., speed, acceleration, and heading). This set of data is the BSM, which the vehicle can then send to another vehicle using a device (such as a DSRC transmitter). Prior to transmission, a security module prepares and processes security information and certificates to ensure that the messages are valid.

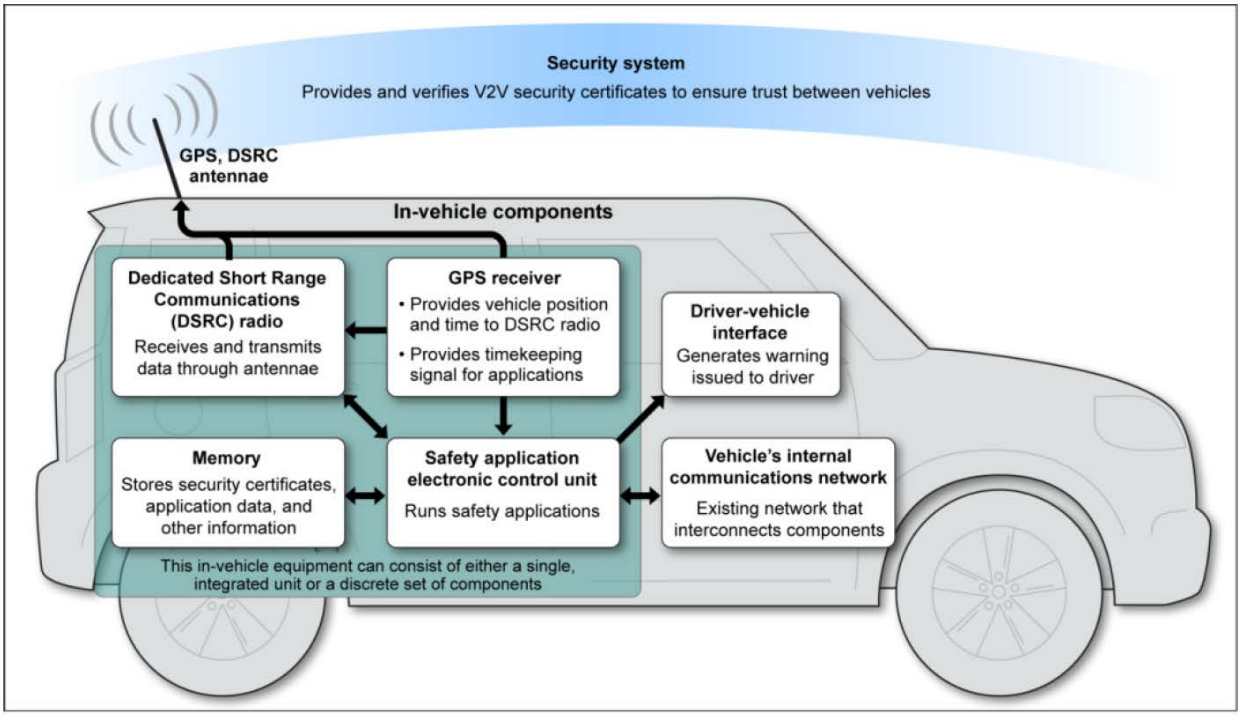


Figure 4. In-Vehicle Components of a CV System (*21*).

Receiving and transmitting BSMs first requires a device that is interoperable with the one sending the initial message. In other words, if the first message is sent through DSRC, the second vehicle must be equipped with a DSRC receiver as well. The receiving vehicle also needs a computer to process the information and GPS hardware to verify the relative distance between the point of transmission and receipt, and the vehicle must also have a security module to verify the validity of the message.

The CV system, as currently envisioned, would communicate information and warnings to drivers through a user interface known as a driver-vehicle interface, although this interface has not yet been designed or tested (*21*). The device will likely include some combination of a heads-up display, LEDs and blinkers, auditory warnings, and haptic feedback.

Software

Applications for CVs generally fall into four categories: environmental, mobility, safety, and support applications (*22*). Each of these broad areas can be further divided into subcategories, and many of those subcategories have multiple associated applications. In total, there are nearly 90 applications across the four areas. This section provides an overview of each area and discusses some salient examples of the applications.

Environmental Applications

Environmental applications of CV technology either reduce the environmental impact from driving or address issues related to road weather. The applications related to reducing the environmental footprint of driving are included under the USDOT's Applications for the Environment: Real-Time Information Synthesis (AERIS) program, which aims to "generate and acquire environmentally-relevant real-time transportation data, and use these data to create actionable information that support and facilitate 'green' transportation choices by transportation system users and operators" (*23*).

A group of applications, called eco-signal operations, illustrate the AERIS applications (Figure 5) (*24*). These applications use information transmitted between vehicles and the infrastructure at intersections to reduce fuel consumption and greenhouse gasses. The eco-approach and departure at signalized intersections application analyzes an intersection based on an information exchange with an RSE (through V2I) and any nearby CVs (through V2V). Using the information received, the vehicle calculates the optimal approach speed to move through the intersection, advising the driver how to adjust his or her speed to move through the intersection in the most eco-friendly manner. The application also analyzes a vehicle's speed as it departs the intersection and allows the driver to adjust driving style to improve fuel efficiency.

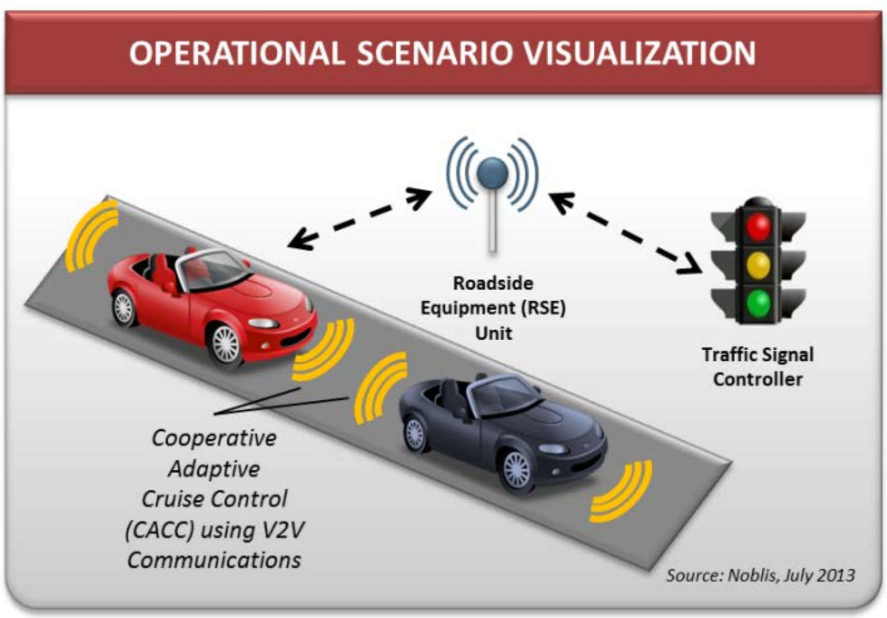


Figure 5. Eco-Approach and Departure Application (*24*).

Mobility Applications

Mobility applications serve a diverse set of functions but are all aimed at improving mobility. This improvement is accomplished through applications that enable drivers to identify a faster route, drive more efficiently, and make better-informed choices (*25*). Mobility applications also provide information to transportation agencies, allowing them to better manage traffic, transit operations, and parking facilities. The mobility applications are arranged into 11 subgroups:

- Border.
- Commercial Vehicle Fleet Operations.
- Commercial Vehicle Roadside Operations.
- Freight Advanced Traveler Information Systems.
- Miscellaneous.
- Planning and Performance Monitoring.
- Public Safety.
- Traffic Network.
- Traffic Signals.
- Transit.
- Traveler Information.

Dynamic speed harmonization, an example of a traffic network application, enables vehicles to "change traffic speed on links that approach areas of traffic congestion, bottlenecks, incidents, special events, and other conditions that affect flow" (Figure 6) (*26*). Harmonizing vehicle speed under such conditions can help maintain traffic flow by reducing the occurrence of unnecessary stops and starts. The application draws on both V2V and V2I to communicate with both vehicles and the infrastructure.

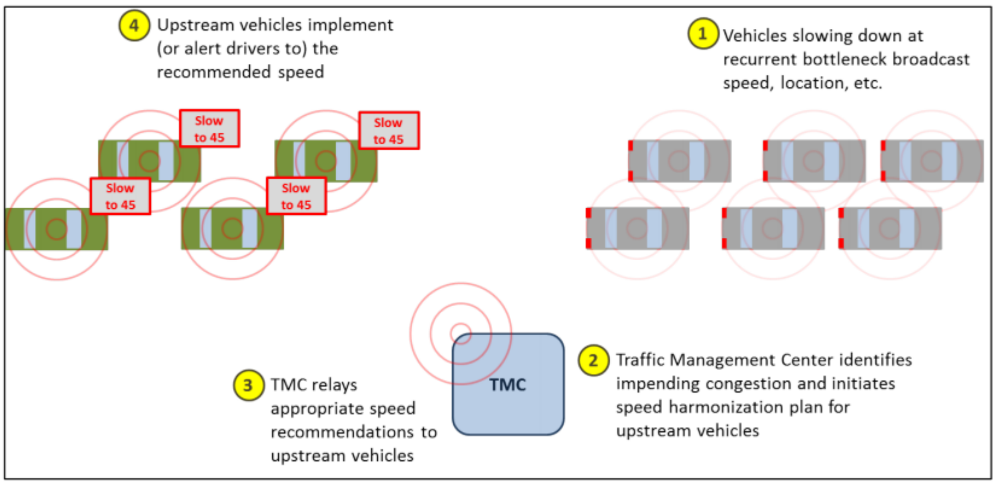


Figure 6. Dynamic Speed Harmonization Illustration (*26*).

Safety Applications

Safety applications consist of those applications that logically aim to decrease crashes and improve safety. The 26 safety applications are grouped into three broad categories:

- Transit Safety.
- V2I Safety.
- V2V Safety.

To illustrate a safety application, Figure 7 shows how the V2I safety application called stop sign gap assist (SSGA) could improve safety in a fictitious city (*27*). The SSGA application is designed to improve safety in rural areas where a major road is intersected by a minor road with a stop sign present. The application uses V2I data to help drivers at the minor road stop sign "understand the state of activities associated with that intersection by providing a warning of unsafe gaps on the major road. The SSGA application collects all available sensor information (major road, minor road, and median sensors) data and computes the dynamic state of the intersection in order to issue appropriate warnings and alerts" (*28*).

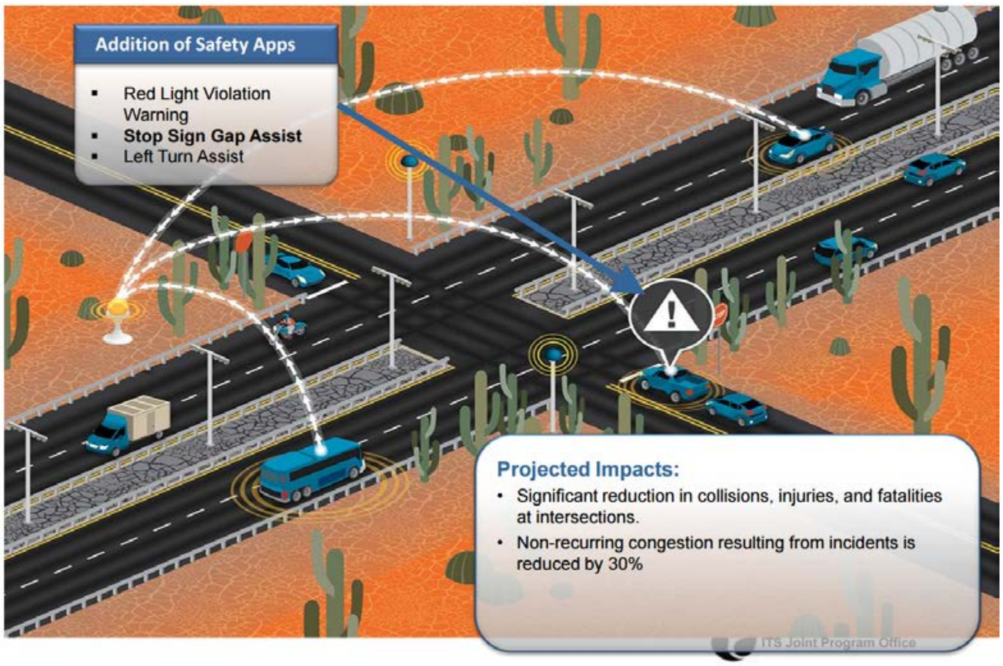


Figure 7. Stop Sign Gap Assist Concept Demonstration (*27*).

Support Applications

Support applications are distinct from the other categories because these applications provide the underlying services that enable the connected vehicle system to run (*22*). Support applications are not consumer facing and are grouped into three categories:

- Core Services.
- Security.
- Signal Phase and Timing.

As an example, the core services infrastructure management application "maintains and monitors the performance and configuration of the infrastructure," which includes "tracking and management of the infrastructure configuration as well as detection, isolation, and correction of infrastructure service problems." The infrastructure management application also monitors infrastructure performance.

Expected Development Path

CV technology has been under development by the federal government, in coordination with others, for nearly a decade. Continued leadership from the federal government is expected to lead to a nationwide rollout of a DSRC-based CV network in the next 10 years. Similarly, the CV rollout will also require coordination between government agencies, across all levels of government, and with the private sector. The federal government will take the lead in implementing the V2V component, which requires finishing the technology and moving it through the regulatory process. Vehicle manufacturers must then meet the regulatory requirements and install the equipment in their vehicles by the deadline. State and local government agencies will then need to deploy and operate CV systems, especially the V2I components, across their jurisdictions.

Federal Regulatory Process

The expected development path for the connected vehicle system is initially tied to the regulatory process at the federal level. To implement the connected vehicle system, the federal government will eventually mandate that all new vehicles must have the required DSRC hardware. To that end, NHTSA recently released an Advanced Notice of Proposed Rulemaking (ANPRM). The ANPRM announced the agency's intention to eventually mandate the technology on all new vehicles (*29*).

The regulatory process is complex, and the ultimate timeline for completing the rule mandating the technology is uncertain, although U.S. Secretary of Transportation Anthony Foxx has stated that he expects NHTSA will "have a proposed rule requiring the technology by the end of this year [2015], and a final rule in place by the end of 2016" (*30*). The uncertainty in the process, however, is due to the need for the agency to have periods for public feedback and to review the public's opinion on the proposed regulation. The rulemaking process began with the ANPRM, and NHTSA is currently preparing the Notice of Proposed Rulemaking (NPRM) (*31*). Once the NPRM is complete, the agency must hold a period of public comment, revise the rules if needed, potentially have another period of public comment, and then compile the rule and related materials onto the public docket. The agency then could publish the rule, revise it with another proposed rule, or withdraw the proposal. If none of these things occurs, the rule could then go into effect, but only after a final 30-day waiting period.

There are additional, non-legislatively required steps that the agency could decide are necessary. These include the ANPRM (like NHTSA already used), additional requests for public comment, Supplemental Notice of Proposed Rulemaking, Interim Final Rules, public meetings, or hearings. These additional steps would further delay a final rule-making announcement and the subsequent deployment steps.

Steps to Deployment

While NHTSA has the regulatory authority to require safety equipment in new vehicles (like DSRC), it does not have the authority to require that states implement V2I systems. Implementing V2I would require states to install RSE and other support systems, which is beyond NHTSA's regulatory authority. It would also represent a large financial burden for state or local governments.

The USDOT's report on CV footprint deployment scenarios describes how state transportation agencies could deploy CV programs. First, a state would "identify the needs and appropriate deployment opportunities" (*32*). Under this step, USDOT recommends that states should develop strong institutional awareness and support for potential local and/or regional deployments. This action is important because the CV program will likely benefit travelers that span political jurisdictions, and agencies will need to cooperate and collaborate to ensure the program's benefits do not end at political boundaries. USDOT also encourages states to "consider the externalities of and alternatives to a CV application deployment" to ensure that the technology is the best approach for a specific circumstance (*32*). Certain factors will affect the efficacy of CV systems, like the number of DSRC-equipped vehicles in a given area, the density of cellular coverage, or the existence of redundant intelligent transportation system (ITS) equipment.

States are advised to consider a local demonstration project. According to USDOT, such a project would clearly demonstrate the value of a connected vehicle program in a specific local environment. The demonstration could help sway skeptics and build the coalition needed for full implementation.

Following this stage, the steps to deployment would be similar to those of standard ITS deployment processes: the use of a long-range plan would establish the vision and broad plan for coordinated action, and a five- or seven-year program and transportation improvement plan would establish the plans for near-term deployment. Other than some technical details like registering roadside equipment with the national security system, the process is very similar to implementing ITS. Finally, the agency would need to perform some staff training and development to ensure employees are equipped to operate the new system.

Connected Automation: Converging or Colliding?

Both connected and automated vehicles are advanced vehicle systems, are maturing technologies, and have the potential to improve transportation safety, mobility, and accessibility. Although the development timelines and deployment scenarios are uncertain, it is clear that convergence of AV and CV technologies, and with other communications technology, is necessary in order to realize the full benefits to an automated transportation system.

CV development has been spearheaded by the federal government and will require close collaboration between governmental agencies and private industry to achieve the potential benefits. It provides a communications platform that vehicles and infrastructure can use to relay information in real time that can reduce crashes, improve mobility, and improve environmental outcomes. It functions primarily by giving information to drivers (or other road users), who then act on the information. CV technology is designed to provide information gathered from the environment to road users, who can then decide to act on the information provided to them. CV technology does not control vehicles or any part of the driving task.

AVs do, however, control the vehicle—an important distinction from CVs. In addition, AVs are primarily a product of private development; the technologies are proprietary, and automotive companies are all racing to develop their vehicle first. Vehicle companies are developing their systems independently, and there is no single, unified AV system; the way one AV functions could potentially be different from the way another AV functions.

Because of these different development paths, the role of public and private stakeholders, and the function of each technology, it is unclear how CV and AV technology will interact or perhaps interoperate. Both systems are not yet mature, and there is a high amount of uncertainty regarding the final form and functional capabilities of different AVs. Because of this uncertainty, it is unknown how the systems will compete, complement, or collaborate to achieve similar goals. Examples of how AV and CV technology can work together already exist. CACC is an extension of ACC, an AV technology in which an AV regulates the distance from the vehicle ahead. CACC takes information gathered from other nearby vehicles and infrastructure to improve the precision and quicken the response time of the vehicle.

Automotive companies, for example, have already expressed their hesitance to incorporate CV systems in their vehicle due to uncertainty regarding liability issues. The industry fears that it could be difficult to determine who should be held liable for "a V2V system failing to perform as a driver expected, due to the complexity of the system and the number of parties involved" (*21*). The Vehicle Infrastructure Integration Consortium, an automotive industry group, also argues that there is no "contract, legal mechanism, or case law to provide courts with guidance on risk allocation" (*21*). Many similar technical, legal, and organizational issues remain to be addressed. Successful implementation of the CV system may depend on how issues like these are resolved, especially once vehicles become highly automated.

CONCLUSION

There is much speculation regarding AV/CV uptake and the potential impacts on individual travel behavior and the transportation system. AV and CV technologies are upending expectations about how people interact with and use personal vehicles. For transportation planners, potential benefits include fewer crashes, reduced congestion, increased roadway capacity, and financial savings. AV/CV technology has the potential to influence many aspects of the transportation planning process, from assessing existing needs, forecasting future needs, and making decisions about projects and the most efficient use of funds. This review of the existing and expected technologies is a critical first step in an effort to project possible future scenarios.

Current AV technologies are rapidly improving and are making their way onto a growing share of the vehicle fleet. The current technologies are generally limited to either providing information through warnings or intervening in limited situations to either prevent crashes or improve mobility. As these technologies improve and grow their market share, the benefits from automation will ripple throughout the vehicle fleet. The effect that automation will have on travel behavior and planning is uncertain and is a topic of investigation for future research tasks.

CVs are similarly poised to dramatically improve the driving task by making it safer, cleaner, and more efficient. The CV applications, enabled by DSRC hardware, provide benefits in many specific circumstances, like the stop sign gap assist, as detailed above. As NHTSA moves through the regulatory process of mandating CV hardware on new vehicles, states will likely bear the burden of implementing the roadside infrastructure components. The CV system can provide many benefits with only V2V, but the cooperation and collaboration of different stakeholders will likely affect the program’s overall success.

How connected and automated systems will eventually interoperate is uncertain. Opportunities for these technologies to complement each other and provide additive benefits abound, like in the case of CACC. Ultimately, the integration is uncertain and will partially depend on how different stakeholders respond to the opportunities and challenges presented by these advanced technologies.

CHAPTER 3. POTENTIAL IMPACTS OF AUTOMATED/CONNECTED VEHICLES ON PERSONAL TRAVEL

INTRODUCTION

According to the Texas State Data Center, the population in Texas in 2010 was 25 million persons (*33*). An additional 29 million people are projected to be added to the state's population by 2050, representing a 116 percent increase over 2010. Of this total, over 75 percent of the growth will occur in 15 counties across the state, all of which are urban or suburban. Eighty-eight percent of the total 2010 Texas population is within the 25 metropolitan statistical areas. By 2050, 93 percent of the population will be within these urban regions. Ninety-six percent of the growth (over 28 million people) will be added to the 25 metropolitan statistical areas in Texas by 2050 (*33*).

Between 1990 and 2014, total mileage of roadway capacity added in Texas grew by 7 percent. Over that same period, population grew by 55 percent (*34*). If these trends continue, population growth and associated travel demand will grow much faster than the state can add capacity to the transportation system. The growth in demand will not be accommodated by a similar growth in capacity, resulting in even greater congestion than exists today.

Automated vehicles and connected vehicles may offer a way for society to accommodate growth and lack of roadway capacity expansion in a very efficient way that reduces crashes and vehicular fatalities, improves congestion, and expands economic opportunity.

AV/CV and related technologies are evolving in many ways, and the ultimate design, public adoption, and implementation of this potentially transformative technology remains subject to speculation. However, it is clear that the expected advancement and convergence of AV and CV technologies, and implemented in a vehicle sharing environment, could form an integrated automated transportation system that would have transformational changes on personal transportation. Advances in personal communications technologies that provide instantaneous, real-time data to travelers will also play a role in changing the face of mobility. This chapter discusses some of the potential impacts of advanced AV/CV technology with respect to personal travel behavior, urban form, and other aspects of the transportation system.

Personal transportation can be thought of as a system of individual mobility choices made to accomplish a set of chosen activities. Choices by individuals include an array of options such as the need for the trip, the ultimate destination or set of destinations, the modes/vehicles to be used, the time of departure and need for arrival at each location, and many others. Individuals make these choices by looking at characteristics of the trip, such as the availability, cost, and convenience of each choice.

At the present time, AV technology and the highly connected environment in which it is expected to operate present a complexity that is difficult to discuss without being specific. The diversity of technology requires that researchers get specific about goals, the driving environment, and the complexity of the technological environment in which operations take place in order to fully discuss the technology's potential to affect travel behavior (*35*).

AN AUTOMATED PERSONAL MOBILITY ENVIRONMENT

When discussing AV/CV technology, researchers should include a discussion of a comprehensive set of technological advances that, when taken as a whole, could create an automated personal mobility environment (APME). Some have called this the convergence of AV, CV, and infrastructure. Others have referred informally to the grouping of technological advances as a smart ecosystem, or smart transportation ecosystem.

Three Legs of an APME

As Figure 8 illustrates, an APME would include elements of technology and social patterns that grow from existing trends in the following areas:

- AV/CVs and infrastructure.
- Personal communications and information technology.
- The shared economy, the gig economy, and other potential socioeconomic changes.

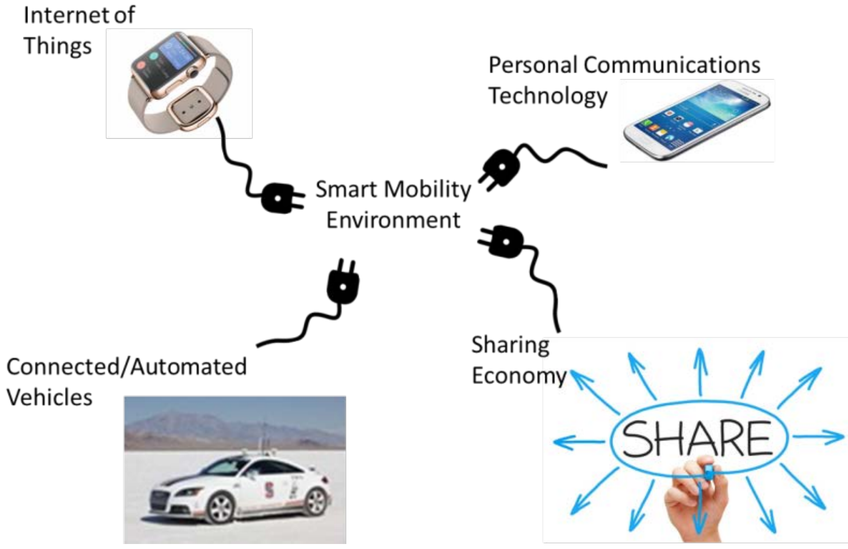


Figure 8. An Automated Personal Mobility Environment.

AV/CVs and associated infrastructure will create a massive amount of data about the location, speed, direction, destination, and occupancy of AVs across a transportation network. These data will not be limited to existing, real-time readings of vehicles at the present moment but will also include future trip plans of individuals. These data could be used in real time by the AV/CV system to ensure that vehicles travel in a coordinated fashion, avoiding overloading the available capacity at busy intersections. A data-driven, coordinated system of vehicles and traffic signals could reduce the system inefficiencies currently created by travelers making independent decisions. Additionally, this information could be processed to provide information to users of the system, providing metrics indicating the optimal cost, mode, route, and other information. Users could then choose the parameters of their tours based on the available information while a coordinated system optimized each individual’s choices, ensuring an effective level of system performance.

Advances in both AV/CV technology and personal communications will need to fully inform the traveler. A fully informed traveler would have the knowledge about system conditions, the availability of capacity, and the travel time required to accomplish a set of activities, all before making the necessary choices of vehicles, routes, time of day, and other traveler options including cost.

Traveler Information

In the current realm of transportation, travelers are not well informed about the parameters of their trips and tours as they actually happen. Although services such as television traffic reports and online traffic cameras are available, travel options are selected prior to initiating the trip/tour. By the time a traveler gets to a specific part of a trip, conditions may have changed. For instance, an incident may have occurred and caused congestion that was not there when the traveler previously accessed the information on the traffic report.

Current traveler information accessed by users through television, the Internet, and smartphones also lacks specificity that a user can reliably incorporate into their trip and tour plans. Without coordinated knowledge of the specific future position of other vehicles and the condition of traffic signals (green time during a cycle), users can only make modestly informed route and time-of-departure decisions. Although several smartphone apps are generally informative about system conditions, and others model future conditions, these apps are ineffective at providing system-level efficiency. System-level efficiency can only be gained if specific trip conditions, such as the location and speed of each vehicle, and system conditions, such as the green cycle of traffic signals along the chosen route, are coordinated.

An APME could bring about a greater reliability in the information being provided to the traveler before a set of choices about the trip/tour is selected. Although random incidents cannot be predicted with 100 percent accuracy in advance, a reduction in crashes would be expected as part of AV technology that would improve the ability of an APME to accurately inform a traveler.

The method of communication of information about system conditions, the various travel options available, and the cost of a tour could become highly efficient through the use of advanced personal communication devices. Currently, smartphones cannot be accessed safely while driving. AV/CVs that self-drive allow travelers to safely access current information on their travel options. The method of communication, whether it be via voice, touch, or gesture, is not a concern here. The important point is that the systems will most likely evolve to become safely accessible by travelers in vehicles, allowing more timely choices among dynamic travel options.

SOCIAL CHANGES AND AV/CV TECHNOLOGY INFLUENCING MOBILITY

AV/CV technology is not evolving in a vacuum. At the same time these vehicle technologies are being developed, other transportation trends are emerging, driven by the increasing prevalence of wireless Internet, GPS, mobile devices, and other advanced technologies.

The sharing economy and the gig economy could have profound effects on personal transportation. The sharing economy is a term used to describe the sharing of resources in a manner that benefits two or more people. The motivation behind sharing resources is simple: to maximize the utility of the resource while minimizing each individual’s cost. In transportation, smartphones allow users to communicate their need for mobility through peer-to-peer exchange apps.

The gig economy may also become a more prevalent influence on transportation. The gig economy refers to a shift from workers being employed as employees of a firm or agency to workers becoming more independent, serving clients directly, much like independent contractors or freelance workers. This concept may include organizations that provide human resources, much in the same manner that employment agencies do today.

Shared Mobility

Examples of shared mobility include transportation network companies (TNCs) such as Uber®, Lyft®, and RideScout®; all of these use smartphone apps to inform potential travelers about travel options, including time, cost, and availability. Other examples include Car2Go® and ZipCar®, which are services that share vehicles through a subscription service or club. These concepts also include B-Cycle® and other bicycle sharing services.

Shared mobility programs have functioned at some level in the United States for decades. In recent years, numerous public bike-sharing programs, car-sharing networks, and private ridesharing have opened in urban markets. The growth of these programs and services suggests that there is a demand, at least in cities, for flexible, on-demand transportation. Like AV/CV technology, the future of shared mobility programs is uncertain but will be shaped by public policy and market demand.

Shared mobility may be characterized by the following categories:

- Ridesharing and ride matching—a more traditional form of carpooling, with drivers and occupants organizing and sharing a vehicle provided by an employer or a transit authority, or using one of the group’s private vehicles.

- Dynamic ridesharing—using smartphone apps (such as Carma®) or computers to access vehicles and share rides with drivers already on their route to their destination. Dynamic ridesharing can be further sub-classified as:
    - Private, informal, dynamic ridesharing, which also can be called slugging, where carpools of riders are formed at formal or informal stations, usually not using computers to link up riders with drivers. These arrangements are most common among users of priced lane systems in order to reduce or eliminate the tolls.
    - Commercial TNCs and taxis, where a private company, such as Uber or Lyft, matches paid drivers with riders based on a commonality of destination matched by GPS through a smartphone app.
    - Autonomous dynamic ridesharing, also called shared autonomous vehicles, is dynamic ridesharing but through the use of driverless vehicles, as envisioned currently. This mode has also been called RoboTaxi and aTaxi (autonomous taxi).
- Car sharing, which can be categorized as follows:
    - Subscription vehicle services such as Car2Go or ZipCar that are similar to vehicle rental but differ in that users (drivers and riders) subscribe to the service and have access to vehicles owned by a private company. Subscribers pay a base fee and a per-trip fee for each use.
    - Private car sharing is simply the concept of sharing the ownership and use of a vehicle based on residential and work location and usage patterns. This type of ownership and vehicle sharing may become more popular for older individuals that do not have a daily need for a vehicle and have infrequent trip-making patterns.
    - Autonomous car sharing, which is essentially the same as car sharing but with driverless vehicles. If autonomous vehicles become more costly to maintain and use than current autos, this may be a way to reduce the cost of auto ownership to each individual.

Ride-providing services, including TNCs such as Uber and Lyft and on-demand ridesharing services such as Carma, have emerged recently, providing travel options that address some of the challenges of early carpooling. Traditional carpooling peaked around 1980, when about 20 percent of workers carpooled, and decreased to under 10 percent in 2013 (*36*). Dynamic ridesharing services such as Carma are similar to traditional carpooling but take advantage of wireless connectivity to better connect riders and drivers, offering easier ride matching and more flexibility. TNCs operate more like a taxi service than a carpool, using smartphones to provide seamless communication between a growing pool of drivers and travelers. Because services such as Uber have expanded to hundreds of cities worldwide, answering the question of how cities, states, and local governments will regulate the programs will be a major factor in their future.

Car-sharing programs offer short-term access to a vehicle without the costs or responsibilities of personal vehicle ownership. Users typically pay to be a member of the program, granting instant access to a pool of shared vehicles and usage fees that include insurance, gas, and reserved parking. Industry studies have suggested that car-sharing program users may sell or forgo purchasing a vehicle as a result of their participation in the program, but the aggregate impacts of car sharing are otherwise not well quantified.

Car sharing also shifts the costs of driving to a pay-as-you-go system in which the true costs of a trip are monetized into a minute, hourly, or daily rate. Some research suggests that this can lead to decreases in overall vehicle travel since users are incentivized to weigh the costs of an individual trip using different travel modes. Like other shared mobility services, car sharing is limited outside of major urban centers. Peer-to-peer programs, where car owners can share their vehicles with other drivers, may better serve less urban regions.

These new shared mobility services have been embraced by a growing number of users in a diverse set of cities around the country. Most of these users are located in dense, urban areas where the use of public transit and other alternatives to driving alone are already more common. Technological advancements have made these services more convenient and attractive for users, generating increased demand for car sharing not only from individual users but also from traditional car rental companies, vehicle manufacturers, and technology companies. The potential of these shared mobility services to become a major part of our national travel activity is unclear, and today, they remain a small fraction relative to motor vehicle travel. However, the success of these programs suggests there is demand for flexible, on-demand travel.

Bike Sharing

In 2008, Washington, DC, was the first major U.S. city to launch a bike-sharing program. Since then, dozens of other cities, including San Antonio, Fort Worth, and Austin, Texas, have initiated bike-sharing programs. The current generation of bike-sharing programs uses GPS and mobile devices to improve on earlier systems with better security, instantaneous access, electronic payment, and real-time user information. Bike sharing is typically aimed at trip activity in dense urban areas, for short-distance trips, and for recreation or tourist activities. The rapid expansion and popularity of bike sharing may indicate a demand for non-motorized travel, but the suggestion that bike sharing can operate as a complement to or substitute for transit is not yet established in practice.

Impacts of Shared Mobility on Behavior and Planning

AV/CV technology and shared mobility services are evolving today in parallel and could be part of various future scenarios for travel behavior involving shared vehicles. Shared mobility and AV/CV technology could impact:

- Auto ownership.
- Vehicle utilization and parking requirements.
- Trip spontaneity and the realization of travel costs.
- Short trip making.

Many visions of a future with AV/CVs include the possibility of a shift away from personal vehicle ownership toward a shared mobility marketplace. It is estimated from household travel data that an average driver spends 5 percent of a day driving, and the car is parked the other 95 percent of the day (*37*). Car- and ridesharing models may reduce this inefficiency by decreasing the amount of time a vehicle is left idle since it is shared among multiple users. An autonomous vehicle that requires no driver could further this system by enabling the car to drive itself between different passengers.

Shared vehicle use could reduce the spontaneity of trip making (the marginal costs of each additional trip are higher and more transparent than for a personal vehicle) and reduce trips made by car in general. Because of the reduced spontaneity caused by a consideration of immediate cost of each trip with shared-ride services, short trips currently made by personal vehicle may shift to walking or biking. While car sharing is expected to reduce trip making of individuals, autonomous vehicles could counteract this reduction due to the repositioning of driverless cars to optimize pick-ups and drop-offs. On the other hand, if AV/CVs arise in a travel environment that is more multimodal, including ride sharing and bike sharing, then the distribution of travel mode may include less driving alone and more alternative modes overall.

Shared mobility and AV/CVs pose a myriad of complex issues to the planning process. As options increase for travelers, agencies responsible for planning will need to have access to additional data that describe the various modes, routes, vehicles, and other options that travelers are choosing. Additionally, planners will want to know the rationale behind the choices that travelers are making, given the improved information and expanded choice sets presented to each traveler for each trip or tour.

GOALS FOR AN APME

The goals of an AV environment were classified into the following categories by Steven Schladover in a July 2015 webinar sponsored by USDOT (*35*):

- Increasing comfort and convenience.
- Reducing time spent driving.
- Reducing user costs.
- Reducing travel time.
- Improving safety.
- Enhancing mobility options.
- Reducing traffic congestion.
- Improving efficient use of infrastructure.
- Reducing future cost of infrastructure and equipment.

Added to this list could be the goal of reducing labor costs associated with chauffeuring services, such as taxis, on-demand ridesharing services, and public transit. Past automation through the use of advancements in technology has dramatically changed the amount of labor required for other transportation services. Standardized containerization of freight has allowed for automation of loading/off-loading at transfer points and shipping docks, dramatically reducing labor requirements.

Other goals could be to more efficiently use fuel and reduce vehicle emissions. Computer-controlled vehicles can be programmed to accelerate and decelerate with much greater efficiency than drivers. This may save significant amounts of fuel and enable longer ranges for electrically powered vehicles. A direct effect of greater fuel efficiency is a reduction in pollutant emissions, thereby improving air quality.

Freight movement, economic vitality, and environmental sustainability can all be improved under future scenarios that include an APME and AV/CVs. Any type of efficiency obtained through AV/CVs in routing and the reliability of deliveries will improve freight logistics, lowering cost and improving economic outcomes.

Environmental sustainability can be improved by AV/CVs as well. Efficiently accelerating/decelerating and minimizing stops/starts can yield better fuel efficiency, which in turn yields better sustainability.

POTENTIAL AV/CV OPERATING ENVIRONMENTS

The operating environment will play a key role in how automation is implemented. These environments may be closed circuits, exclusive guideways, parking structures, restricted sections of cities, or open-operating environments. Parking garages, grade-separated roadways, closed circuits on campuses or at airports, exclusive zones such as downtown areas, or specific corridors may have different requirements. The degree of fixed guidance and channelization will require different levels of automation to ensure safe operation. Also, decisions on the degree of human control will play a role in the level of automation required for a specific operating environment.

AV/CV technology above NHTSA Level 2 is not currently publically available. In 2012, the average auto ownership time for new vehicles was 71.4 months (six years), and for used vehicles, the length of ownership was 49.9 months (four years). Data from R.L. Polk show that the average age of cars and light-duty trucks in the United States was 10.8 years in 2011 (*38*). Since AV/CV technology will take time to be absorbed into the marketplace, planners need to monitor the expected trend of market adoption of AV/CV-equipped vehicles into the U.S. fleet. During this adoption period, various levels of implementation of AV/CVs will undoubtedly surface.

Implementation of AV/CVs will probably have various degrees of human interaction, deployment areas and types, and ownership. One way to categorize these potential implementations is as follows, and as summarized in Table 7:

- Driver-assisted automation, where a driver/chauffer is present in the vehicle and can take control of the vehicle at any time (Level 3). This type might be suitable for personal use vehicles that transit into and out of automation-restricted or automation-available areas of a city. Currently, engineers are concerned about this type of implementation, particularly in the experience of Google, who currently has the most on-street hours of any autonomous vehicle test program in the United States. There will need to be more research into the safe transition of vehicle control between the driver and driverless mode, and some method to ensure driver attentiveness in monitoring system functions.
- Driverless, monitored transit services (Level 4). This type of automation may be suitable for public transit operating environments, such as city buses or shuttle services at airports and other venues. It may be necessary to have system monitoring personnel, who could be stationed in a remote control center, along routes, or at specified stops. Currently, there are rail transit systems that operate in this fashion, such as the Vancouver, B.C., SkyTrain.
- Private autonomous vehicles (Level 4), operating independently and privately owned or shared with a small set of authorized users. Owners would be responsible for vehicle maintenance and operation. It is important to characterize the ownership of vehicles (since it defines accessibility to the vehicle) and the subsequent utility of the vehicle for mobility. Cars in this category may operate without a driver or passengers, but only for a more limited duration, because they are only seeking to pick up qualified owners (such as moving into and out of parking areas).
- Common-use shared autonomous vehicles (Level 4), operating as part of a fleet service provided by a public agency or private firm that specializes in mobility services. Human interaction would be limited to system management and maintenance services/facilities. This category represents a system of shared autonomous vehicles. These vehicles would need to operate independently (no passengers) and extensively to serve passengers, and one simulation of this type of activity shows that a significant amount of vehicle miles of travel would be created because of this passenger-seeking mode of travel (*39*).

Table 7. Potential Operating Environments for AV/CVs.

	Driver-Assisted	Monitored Fleet	Private	Common-Use Shared Fleet
Technology	Level 3+	Level 4	Level 4	Level 4
Driver	Driver required to take over	System monitor required	No driver required	No driver required
Typical Use	Automation-available and automation-only areas; requires transition from driver to vehicle control	Public transit, shuttle services on fixed routes	Private ownership, vehicle sharing restricted to small group of authorized users; auto occupancy equivalent to current levels	Common-use subscription or general on-demand services; shared vehicles and shared rides

AUTOMATION AND HUMAN RESOURCES

There is no case being presented whereby humans are not involved in a controlling aspect of AV/CV technology. Although Level 3+ does not require *driver* intervention, the level of automation implied by this level requires that human intervention take place in a programmatic mode, rather than an operational mode. Humans would remain involved in the provision of mobility, although remotely and indirectly.

Other than driving, human interaction within an AV/CV transportation system would be in several areas:

- Programming—software to control an AV/CV system will be significant and require debugging, monitoring, and updating.
- Monitoring—humans will be needed to monitor common-use AV/CV systems, ensuring functionality and prevention of and response to vehicle and system misuse. Also, there may be a need to have customer services, such as for payment problems, for commercial, common-use, shared AV/CV applications. Policing services may also be required for some common-use applications to ensure security, much like transit systems have today.
- Maintenance services—fueling, cleaning, repair, and general maintenance services will require labor as well.

POTENTIAL TRAVEL BEHAVIOR IMPACTS OF AV/CV TECHNOLOGY

One way of thinking about travel behavior and AV/CV technology is to examine the car in its full context as a component of everyday life rather than strictly a utilitarian tool for transport. In fact, auto manufacturers sell many communications features on cars to add more functions than simply transportation. There are several ways in which AV/CVs could influence travel behavior:

- Improving safety could eliminate non-recurrent delays due to crashes in congested corridors, thus making the transportation system more reliable, enabling better trip planning, and allowing for alternate uses of time that is currently spent in traffic jams.
- Coordinating flow by platooning AV/CVs and reducing or eliminating delay at traffic-controlled intersections could improve overall capacity and reduce or eliminate congestion.
- Removing the driving task will free passengers of autonomous vehicles to perform other activities during a trip. Trips may be eliminated if the activity could be performed in an autonomous vehicle. This may also change the perception about the value of time spent in a vehicle and prompt a change in behavior that today is driven by the need to minimize time spent in a vehicle.

Potential Safety Influences on Travel Behavior

Much of the current focus on potential transportation impacts of AV/CVs is on safety. Eliminating human errors, improving the responsiveness of the vehicle in situations requiring quick reaction, and controlling the trajectory and speed of the vehicle when the driver is impaired, drowsy, or distracted are some of the ways in which AV/CV technology will help reduce, or eliminate, most crashes.

Infotainment systems within many car models can now connect the driver and passengers to the Internet, read incoming text messages, send common messages through voice commands, let the driver know who is calling on the phone, and perform many other tasks. Unfortunately, the growing amount of functionality in cars is also becoming increasingly distracting to the driving task. Distracted driving results in many crashes, and use of handheld electronic devices in cars is significant, with approximately 620,000 drivers using a handheld device in the United States at any given daylight moment according to the National Occupant Protection Use Survey (*4*). Automation, including fully self-driving cars, offers a solution to this growing problem.

From a travel behavior point of view, improved safety from AV/CV technology may have an objective influence on travel choices. If travelers feel that the technology is safer, they may choose to make more trips or travel at times when they normally would not, such as late at night when they may become sleepy. With AV/CV automation, including when the vehicle can assume the driving task completely (Level 4), the disincentive to travel because of sleep needs may be reduced or eliminated completely.

The largest impact from safety improvements as a result of AV/CVs may come in the avoidance of non-recurrent delays on congested facilities caused by vehicle crashes. Vehicle crashes that occur during peak periods on heavily used facilities can cause blockages in the traffic stream and delay motorists from getting to their destinations. In addition to the delay caused by crashes, the occurrence of the crashes and the associated delay is unpredictable. The lack of reliability hinders the traveler in making optimal choices about route and causes a disruption in their activity plans.

Potential AV/CV Impacts on Trip Making

The primacy of cost related to an activity that requires transportation may be transformed by AV/CVs. This has to do with how AV/CVs may influence ownership and how the cost of transportation is paid. In today's paradigm of private vehicle ownership, most of a vehicle's cost is not directly related to the immediate transportation choices an individual has when deciding on how to access an activity. The perception of cost of each trip is lost at the moment of decision since the vehicle is already paid for, including insurance. The vehicle also usually already has fuel, although the cost of fuel is realized with enough frequency to be apparent to the traveler. Most of the cost of the vehicle will be the same (capital cost and insurance) regardless of whether or not a trip is made.

If widespread adoption of AV/CVs leads to less auto ownership because more people may choose to use shared-vehicle and shared-ride services, the primacy of cost of each trip will become apparent to the traveler. When someone needs to pay for the vehicle's capital cost, insurance, fuel, tolls, and other amenities immediately prior to each trip, or by short-term reservation, then the cost is realized immediately to the traveler. This may cause travelers to place a greater importance on these costs than they would otherwise. Also, cost may then become a consideration in choosing travel options.

In this way, an APME using shared autonomous vehicles would change the way the public pays for transportation. When the cost is per trip, travelers may combine more trips into tours and begin to use smartphone and other technology to optimize their travel activities in order to minimize cost. There may be more linked trip making and fewer trips that originate from home overall.

Also, trip generation may decrease as a result of widespread use of an APME with shared autonomous vehicles that realize cost on a per-trip basis. When each trip is deducted from an individual's bank account, the trip may be compared to the utility of the activity desired and impetus for the trip in the first place. For example, a trip to obtain a $5 taco for lunch may be realized as an overall cost of $15 or $20, which may cause the traveler to reconsider the initial decision to make the trip to obtain the taco and seek an alternative way of getting lunch that may involve walking or biking, or not traveling at all.

Impacts of AV/CVs on Time of Day of Activities

Currently, the choice of time of day to make a trip is influenced by the need to accomplish a set of activities during specific periods. People have priorities in their travel choices, usually centered on work. Commuter and student behavior is driven by work and school schedules. Shopping behavior is driven by hours of store operation and, for workers, available times for shopping before or after work hours or on weekends. The timing of social activity is driven by similar constraints. An interaction within a household, and sometimes between households, for use of available vehicles is common, with adults often chauffeuring younger household members or older adults.

Autonomous vehicles may offer some respite from this complex system of negotiated time use for vehicles. People who cannot drive, due to a disability or age, may be able to use self-driving cars in much the same manner as public transportation. This means that they may be able to make trips at any time of the day, without being dependent on a driver’s schedule of activities.

Work schedules and societal behavior concerning employment, including location, will most likely remain a key factor concerning the time of day of travel, independent from vehicle automation. The need to be at a workplace, to access goods and services, and to interact with others will continue to be reasons that people travel in vehicles. AV/CVs will not independently influence the time of day of travel. Integration of AV/CVs into an APME, together with a change in employment requirements, could allow for better optimization of trips and trip times, reducing the overall time spent in transit from one location to another.

Distribution and Accessibility of Goods and Services

As AV/CV technology improves, other technologies will also improve in parallel over time. Some of this technology will be directed at advertising. The accessibility of the product or service may become a common theme in sales. In the current transportation environment, stores try to display their wares to potential customers by accessing media (newsprint, websites, and television) and by locating stores along major arterials that improve their physical accessibility.

In an APME, minimizing the cost of travel may become more important when accessing goods and services. Increasingly, retail products are being shipped directly to the consumer, as with Amazon retail services. If the cost of a trip is realized at the point of trip making, as with an AV/CV shared vehicle service environment, it may become more cost effective to deliver goods to consumers rather than have consumers go to several different locations to acquire goods and services.

Vehicle Ownership and Availability

Much attention has been spent on the travel behavior impacts of the availability and ownership of vehicles. Auto ownership is seen as a key variable in determining public transportation usage and need for obvious reasons. Ownership and availability, however, need to be examined separately.

Currently, vehicle ownership is correlated to vehicle availability. The exception to this condition is when there is availability of a vehicle by loan or by sharing a ride. Ridesharing has taken on an increasing role with the advent of TNCs, which have been formed through the use of smartphones. TNCs are in some ways a precursor to an increasingly automated personal mobility environment. The combination of TNCs and autonomous vehicles leads to the conceptual vision of fleets of shared autonomous vehicles serving passengers that do not own cars. Therefore, auto ownership and auto availability would become less correlated over time.

Overall vehicle availability may increase if the concept of shared autonomous vehicle fleets is realized. People who currently cannot drive a car due to a disability or other restriction would potentially have greater access to vehicles. Mobility could expand into younger and older populations that currently cannot drive.

The cost of travel would remain a strong variable in influencing travel in an APME with shared autonomous vehicles. If travel becomes more costly than today on a per-trip, per-vehicle basis, it could be expected that the number of vehicle trips would decline since more people would share rides to share the cost. It is unknown at this time how much AV/CV technology will add to the typical vehicle cost. If this cost is high, then shared or subscription ownership and shared rides through TNCs will likely become the norm. While it may seem that increasing vehicle cost and trip cost would cause a decline in vehicle miles of travel, with automation, the opposite could be true.

Trip Length and Urban Form Impacts

The shape, extent, and density of urban areas are defined by the multimodal transportation network. Cities were at first limited in size based on human and horse transportation. Railroads and urban rail next defined long corridors along which urban development took place. The automobile and extensive roadway construction allowed for the expansion of cities farther into the landscape. In the past several decades, urban residents have made alternative choices driven by lifestyle, convenient access to amenities, congestion, travel cost, and environmental sustainability. All of these factors have increased use of public transportation, telecommuting, walking, and biking. These choices have spawned densification of some core areas of cities and specific developments in downtown areas.

AV/CV technology and an APME may cause other changes to urban form. As mentioned previously, the perception of travelers regarding time spent in vehicles going from one place to another may be influenced by the removal of the driving task. If comfort and convenience become characteristics of autonomous vehicles and travelers can put otherwise wasted time to productive use, the opportunity cost of travel will decrease. This would impact the desire to minimize time spent in a vehicle. If this condition occurs, then the average trip length could grow, leading to further sprawl of urban development into rural areas.

However, the opposite condition may manifest as a result of AV/CVs. The friction to travel may become less about travel time and more related to travel cost. If the cost of travel increases, combined with the realization of the cost of travel on a per-trip basis, trip length may decrease because of AV/CV technology. This condition would increase the cost of traveling far away from the amenities and workplaces of a city, causing a densification growth in urban areas.

Potential Modal Impact of AV/CVs

AV/CV technology and an APME will have an impact on what we now know as separate modes of transportation. Public transportation is provided at a cost to the general public to accomplish several societal goals related to mobility. These goals include roadway congestion reduction and provision of mobility to populations with limited or no auto availability. Cost of public transit is regulated in order to maximize the opportunity for mobility of lower-income populations. AV/CV technology, when combined with vehicle and ridesharing mobility, could change the way public transportation is offered and governed by public transit providers.

The need of lower-income populations for affordable mobility will not be eliminated by AV/CV technology and other automation. However, the form of transportation available to lower-income populations could change if the cost of shared autonomous vehicles is subsidized in a similar manner to how public transit is supported today. In effect, shared autonomous vehicles may be more affordable if more travelers share rides and are efficiently allocated to vehicles of appropriate capacity to minimize travel cost. The result could be viewed as either autonomous buses or larger autonomous vehicles that could be functionally identical modes.

Routing, Navigation, and Trip Planning Impacts

An APME that includes a sophisticated system of tools made available to people at low cost could develop as follows:

- User optimized information is currently available through various smartphone apps such as Waze®, Google Maps®, and Metropia®. System-level information is provided through the use of crowdsourcing, which accumulates information from other users of the application and locational information from agglomerations of GPS data and cell location data. These apps will define routes and travel times, but optimization of routing is dependent on user decisions.
- System-level optimization would bring information about system conditions, forecast conditions based on accumulation of all routing information combined from other users, and other information about system conditions (which may be stored from previous days). The system would then suggest routes that appear to be the best choice for the user. This APME level optimization would combine the efficiency of AV/CVs, including autonomous vehicles, with automated trip planning for each user. User input to the routing and speed (allowing for coordinated vehicle arrivals at intersections) would be limited in some manner, probably to a finite set of choices.
- Currently, decisions are made by individual users of the roadway and transportation system. Individuals cannot currently access complete information about their route characteristics, and the system is fraught with a high degree of variability (unreliability), making many choices inefficient. While there is an abundance of passive data being collected through GPS and cell tower location sensing, the prospect of turning the data into useful information and then acting on it in a manner that optimizes route and trip plans is far beyond the capability of most smartphone apps available today. System conditions often change in route, and alternative routes

are difficult to predict and compare with each other. In congested cities, the user is perpetually lost in data and cannot make efficient decisions.

- An APME would be able to access the trip plans of each vehicle and predict where the vehicles will be at any given time in the future. These data could then be used to communicate to a central processing server that could be accessed to form future trip plans. Efficient braking, acceleration, and speed control from autonomous vehicles could then be optimized such that each vehicle encounters little or no interference from other vehicles. Some simulations suggest that with correct timing, autonomous vehicles could reserve space along roadways and in intersections, eliminating the need to stop and yield the right of way to other vehicles, even in the middle of intersections.
- Given an APME, trip planning could become greatly enhanced, relieving travelers of the task of attempting to optimize their plans. This would add a level of convenience to travelers, which could prompt increased trip making.

CONCLUSION

AV/CVs are expected to have a significant impact on personal transportation in Texas and across the world. Technology in transportation planning is expected to have significant impacts, and planners can speculate how things might change, but the data to support these claims are based on limited experimental demonstrations. Widespread deployment in natural operating environments will be needed to determine behavioral impacts.

Experiments in modeling AV/CVs are ongoing to determine potential capacity impacts. Road testing of fully automated (Level 4) vehicles are being performed by Google and auto manufacturers, and are proving to be very successful and safe overall. Travel behavior impacts could be wide ranging, particularly if an APME that combines AV/CVs, personal communications, and a sharing economy comes to fruition.

AV/CVs could impact many aspects of travel behavior. Areas that may be affected include vehicle ownership and availability, public transportation and governance, housing and job location choices, trip-making and time-of-day behaviors, perceptions of congestion, traffic delay and non-recurrent delay, and routing and navigation. All of these aspects could greatly improve the transportation system.

CHAPTER 4. POTENTIAL TRANSPORTATION IMPACTS OF AUTOMATED/CONNECTED VEHICLES ON COMMERCIAL AND FREIGHT TRANSPORTATION

INTRODUCTION

Often forgotten or delegated to an afterthought in the discussion of the impact of automated and connected vehicles are the planning issues associated with commercial and/or freight transportation vehicles. Little direct thought is given to how they will be managed or interact with infrastructure and other vehicles, and the changes in planning processes and system design that may be needed. These impacts could be broad ranging, affecting:

- The overall infrastructure costs.
- The freight routing selection and subsequent commodity costs to consumers.
- The need for separate/specialized freight transportation facilities.
- The number and location of intermodal exchange nodes along the highway system.
- The average speeds at which mixed (freight and passenger) traffic may flow—even in an AV/CV environment.

For this reason, it was vital to include within this project a component examining AV/CV planning impacts on commercial and freight transportation. This chapter presents the results of Task 3, which aimed to study the potential transportation impacts of AV/CVs on commercial and freight transportation.

TRENDS IMPACTING FREIGHT LEVELS

Growing Freight Demand and Capacity Needs in the United States and Texas

As population grows, the prevalence of commercial trucking as a part of the overall traffic mix is also expected to grow. The USDOT's recently released draft National Freight Strategic Plan (NFSP) reports that each day, the U.S. freight system moves over 55 million tons of goods worth more than $49 billion, which equates to over 63 million tons of freight moved per person in the United States annually (*40*). By 2045, the U.S. population is expected to grow from the current 321 million to 389 million, and the size of the economy is expected to double during this same period. To support this growth in population and economic activity, a commensurate growth of freight movements (by all modes) must increase by approximately 42 percent over current levels by 2040 (*40*).

The NFSP also points out that funding and planning of freight infrastructure to achieve these levels will be extremely difficult given the decentralized approach for planning freight improvements. Most planning for these types of infrastructure is done by state and local governments and metropolitan planning organizations—often using federal dollars in conjunction with private-sector partners such as trucking, railroad, and pipeline companies (*40*).

The NFSP recognizes that technological innovations such as automated and connected vehicles and infrastructure are a part of addressing growing freight needs. The report specifically states, "Growth in autonomous vehicle technologies may soon transform freight transportation, allowing for increased throughput and more reliable trips on existing capacity" (*40*). However, even these innovations alone do not address how commercial AV/CVs will interface with the future system. The report also points out that such optimistic population and economic growth projections and forecasts could turn out to be faulty or falter due to adverse economic conditions related to recessionary periods or key commodity price downturns. Despite this inherent uncertainty, the need for inclusion of planning measures for freight-related and other commercial transportation development in the future transportation system is warranted.

In Texas, the draft Texas Freight Mobility Plan (TFMP) released in late 2015 reports that approximately 67 tons of freight per Texas citizen was moved in 2014 over the state's transportation system—4 tons per capita higher than the 63 tons per citizen U.S. average reported above (*41*). Texas's 2014 population is expected to almost double by 2040 from the current 26 million to over 45 million, and projected freight tonnage moved is expected to increase by 88 percent from 2 billion to 3.76 billion tons in that same period.

The largest portion of these goods travels via commercial truck and will result in increased congestion on highways throughout the state, with truck trips growing from 557,000 per day in 2014 to over 1 million per day by 2040 (*41*). While the percentage of trucks varies by roadway and location, special care must be taken to account for the performance characteristics, stopping distances, and operational safety measures required around trucks in roadway traffic when planning for future facility needs—even within a more autonomous and connected transportation system. Special freight traffic generators (e.g., intermodal exchange areas such as inland ports/multimodal exchange areas or seaports) where truck traffic is concentrated should be of concern for future transportation planning.

Changing Delivery Patterns

In addition to growth in the sheer amount of freight movement, the U.S. freight transportation system is undergoing rapid change as e-commerce–based deliveries change how products are delivered to consumers in many freight sectors. Figure 9 shows how many additional delivery options are changing the number of potential en-route and last-mile truck deliveries that might take place.

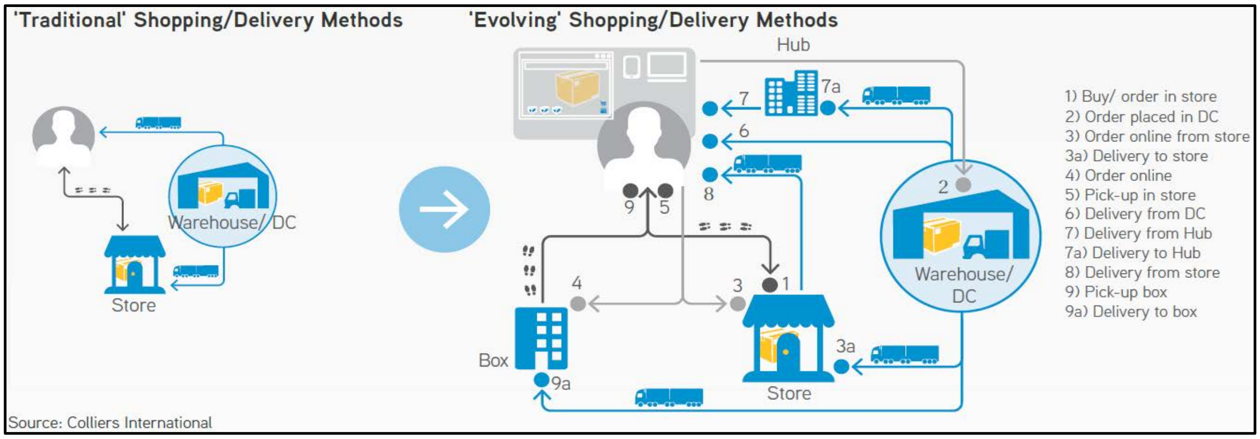


Figure 9. Traditional versus Evolving Shopping and Delivery Patterns (*42*).

While improved data and connected vehicles make such complex delivery patterns possible and more efficient in many ways, the physical space capacity on roadways occupied by trucks moving on infrastructure is not appreciably changed (unless truck platooning becomes a widely adopted standard for all truck movements). Additionally, on-demand one- or two-hour delivery freight services such as Amazon Prime®, which is available in several of the state's major urban areas, may also increase the numbers of trucks or possibly smaller delivery vehicles plying the roadways to deliver freight items. Bicycle couriers, Uber, or similar private vehicle fleets, taxis, and even city buses all suddenly become potential freight delivery vehicles under a connected and/or autonomous system in which any of them can be employed as a means to deliver goods to individuals or to specified pick-up locations.

Changing Distribution Patterns and Urban Form

Growing out of the transition to a more complex and on-demand freight delivery system is the need to change distribution methods and potentially even urban form to facilitate improved freight handling within an urban area or along a supply chain. Strategies such as platooning of trucks or diverting freight deliveries to off-peak highway-usage hours can be improved through better use of data and connected/automated truck features but will not be enough to address overall needs. Changes in urban form might include multi-business or publicly owned large distribution centers (DCs) on urban fringes or located near intermodal yards/airports with a large number of smaller warehouses stocking a variety of items to meet immediate/short-term demand located throughout the urban core. Freight movement corridors may be designated from the large DCs to the local warehouse locations.

Once established patterns are determined, scheduling of automated regular freight movements to resupply the local warehouses may become more common. AV/CV systems that monitor the position of freight movements/commodities throughout the transportation network will also, in theory, aid in scheduling arrivals of these shipments and ensure that the necessary parking space is available at warehouses and other delivery locations.

SPECIFIC ISSUES FACING COMMERCIAL/FREIGHT TRANSPORTATION THAT MAY BE ADDRESSED IN THE AV/CV ENVIRONMENT

Congestion

Congestion issues for freight in the AV/CV environment may be enhanced by system scheduling or use of managed lanes for truck freight only during certain periods of operation or peak freight periods, such as after the arrival of a large container ship at a port area. Specialized guideways or rights of way for automated/connected freight vehicles (such as the Freight Shuttle System) may also remove some highway freight movements, allowing for more efficient use by the remaining freight and passenger traffic.

Capacity Constraints

Several AV/CV features for commercial travel could address infrastructure capacity constraint issues that are either currently being faced or that will result from the forecasted freight growth in the coming decades. Examples would be truck platooning that reduces the headway between trucks, freeing up space on the roadway for other vehicles, and removing freight to specific lanes or off-highway/fixed-guideway routes. Similarly, special lanes for automated commercial buses or bus rapid transit might reduce capacity demand on general purpose lanes.

Driver Availability/Hours of Service

One of the primary challenges facing truck freight movement today is the looming shortage of professional truck drivers. The average age of the truck drivers currently employed, an annual employee turnover rate of between 90 and 100 percent for many trucking companies, and planned retirements threaten to further widen the gap between available truckers and demand for truck delivery. The American Trucking Association (ATA) estimates the current driver shortage to be 48,000 and projects it to increase to 175,000 by 2024 (*43*).

Also impacting truck driver availability are updated federal safety-based hours of service (HOS) rules that limit the number of hours an individual driver may operate before taking a federally prescribed rest period. Cumulative hours also prevent drivers from operating for long periods without taking a required day off for rest. The American Transportation Research Institute (ATRI), a subsidiary of ATA, ranks the driver shortage as the third and HOS compliance as the first most pressing issue affecting productivity in trucking today, according to its 2015 report (*44*).

AV/CV application implementation has the promise of addressing both of these major issues. It can reduce the number of drivers needed to meet future demand and decrease the workload for drivers by automating elements of their work related to both trip planning and vehicle operations while shifting their skills to more observation and correction rather than direct vehicle operations. The human factor/safety issues associated with this transition must also be evaluated in the future as AV/CV operations become more prevalent.

Air Pollution and Emissions

As discussed in the early part of this chapter, demand for freight and commercial transportation is increasing and is expected to do so more rapidly in the coming decades. AV/CV implementation may be able to increase the number of freight vehicles that can operate using existing roadway capacity by reducing headways between vehicles, thus providing better scheduling of deliveries and reservation of parking to reduce idling to address air pollution concerns and comply with emissions limits. Increasing the numbers of trucks operating in a given urban area beyond a certain amount may not be possible, however, unless automated and connected truck fleets are also converted to alternative fuels or more green options.

While AV/CV use may make more trucks technically possible in urban areas, environmental regulations/restrictions may not allow this to take place. The Dallas–Fort Worth, Houston, and El Paso areas of the state are designated non-attainment areas in accordance with the Environmental Protection Agency's Clean Air Act, with several additional areas in "early compact action areas," "near non-attainment," or "maintenance" status. As AV/CV systems are implemented, transition to cleaner fuels or electrical-powered alternatives must be considered to avoid further emissions impacts from increased vehicle numbers and/or operating characteristics that emit at higher rates. Adopting low-emission systems within commercial fleets for trucks and/or transit systems may be more readily accomplished since these vehicles are often operated along regular/fixed routes or on fixed guideways or by public-sector agencies. Future implementation of AV/CV systems will thus need to incorporate emissions planning efforts and thought on how elements of the system will impact overall emissions when they are employed.

Crash Likelihood and Impacts

Crashes between commercial/freight vehicles or between such vehicles and private automobiles tend to have larger odds for producing fatalities and severe injuries compared to crashes solely between private automobiles or light trucks. This is largely due to the greater mass, slower braking characteristics, and higher forces generated by a freight truck involved in a crash. While AV/CV systems will be unable to change the physics associated with the larger vehicle, by proper programming, prohibiting other vehicles from entering a truck's braking envelope, or providing blind-spot warnings to both drivers, an automated or connected system can decrease (or someday eliminate) the likelihood that a crash will occur.

Reducing or eliminating such occurrences can have broad benefits for system movement beyond merely the cost to drivers, trucking companies, and freight load owners. Truck crashes often take longer to clean up and subsequently to restore traffic to normal flow due to spilled loads or fuel tank leakage. Advance notification of a crash location through AV/CV system implementation can also provide upstream freight drivers or loads with appropriate rerouting instructions to avoid problem areas that would lead to delays. In order for such information to be most effective, however, resiliency and redundancy of roadway routes allowing for AV/CV systems to rapidly respond would also need to be planned.

MAJOR FREIGHT PLANNING GOALS AND HOW AV/CV CAN ADDRESS RELATED PLANNING ISSUES

The draft TFMP defines the Texas freight network and operational characteristics for the present day and projected into the future. It includes nine priority goals that are consistent with and designed to comply with the mandated goals of the current surface transportation act, Moving Ahead for Progress in the 21st Century (MAP-21), as well as those in the TxDOT 2015–2019 Strategic Plan and the Texas Transportation Plan 2040. Goals of the TFMP for freight movement in the state also largely follow the concept of the national freight planning goals outlined in the draft NFSP. The nine TFMP goals for Texas freight movement (*41*) and example descriptions of potential AV/CV applications in each goal area are listed below:

- **Safety—Improve multimodal transportation safety.** Safety improvements in all freight modes of transportation covered by the TFMP are desired. These include highway, rail, ports and waterways, aviation, and pipeline safety. Specific AV/CV applications where these modal systems intersect, such as in-car warning that a train is approaching a highway–rail grade crossing or that the warning signals are about to activate, are examples of the type of safety information that the AV/CV environment can supply.
- **Asset Management—Maintain and preserve infrastructure assets using cost-beneficial treatments.** Connected infrastructure that can identify damage or provide maintenance status would be an example of an AV/CV application in this area.
- **Mobility and Reliability—Reduce congestion and improve system efficiency and performance.** As discussed previously, AV/CV innovations such as platooning or reduced headways, the reduction or elimination of accidents, and automatic rerouting of vehicles could all address this freight movement goal and keep goods moving across the system.
- **Multimodal Connectivity—Provide transportation choices and improve system connectivity for all freight modes.** This goal would likely be aided immensely by the amount of information sharing provided in the AV/CV environment. Planning for intermodal transfer and connectivity, ensuring that truck parking and/or dock spaces are available at warehousing facilities, and better managing traffic flows around intermodal hubs such as seaports, airports, rail yards, and pipeline terminals would all be aided by AV/CV system components.
- **Stewardship—Manage resources responsibly and be accountable in decision making.** AV/CV systems would gather and allow planners access to large amounts of information on both freight and passenger movement that would allow better planning of activities and feed into preservation and maintenance planning. For example, high freight traffic routes could be designated and then designed and built to higher standards, allowing longer service life before rehabilitation or replacement

became necessary. This practice could provide better use of assets and lead to cost savings in the long term.

- **Customer Service—Understand and incorporate citizen desires in decision-making processes and be open and forthright in all agency communications.** AV/CV systems allow for the transportation network to be more responsive to user needs. Data collected over time could allow businesses generating freight to identify the best locations and access points to better serve end users on the network.
- **Sustained Funding—Identify and sustain funding sources for all modes.** Again, AV/CV systems would provide information on traffic levels, routing, commodity types, etc. that could be used by planners to justify infrastructure upgrades and/or maintenance funding. Non-highway modes would benefit by being able to recognize patterns of movement that might be shifted to their mode, thereby freeing up roadway capacity and funding for other uses.
- **Economic Competitiveness—Improve the contribution of the Texas freight transportation system to economic competitiveness, productivity, and development.** Improving network flow, addressing truck driver shortages and HOS problems, and improving intermodal exchanges and transfers are all examples of AV/CV benefits that could improve economic competitiveness of Texas on both a regional and statewide basis.
- **Technology—Improve the safety and efficiency of freight transportation through the development and utilization of innovative technological solutions.** AV/CV technologies can advance both the safety and efficiency of the Texas freight system by addressing driver shortages and capacity through platooning, safety through maintaining separation of vehicles and providing proximity warnings of other vehicles, and sharing information on necessary rerouting to maintain system reliability and redundancy.

AUTOMATION IN FREIGHT LOGISTICS

Freight shipments are generally part of a chain of movements from origin to destination. Demand comes from businesses that need to move raw materials, supplies, and finished products for manufacturing, construction, or perhaps customer delivery. Freight carriers provide service by using the available infrastructure to move freight products (*45*). Combined, the components are part of a supply chain, which is defined as a "group of human and physical entities including procurement specialists, wholesalers, logistics managers, manufacturing plants, distribution centers, and retail outlets, linked by information and transportation in a seamless integrated network to supply goods or services from the source of production through the point of consumption" (*46*).

Technology plays a major role in most every aspect of the movement of goods through the supply chain. AV/CV technologies already play a part in certain components and look to further advance the safe and efficient movement of goods. This section identifies how AV/CV is currently being implemented and could ultimately impact freight logistics at various points along the transportation network.

Raw Materials and Agricultural Harvesting

In Australia, the mining industry is currently using driverless trucks to transport raw mining materials from the mine pit to collection point. The use of the trucks in mines allows for the vehicles to operate in a closed environment under high-risk situations (*47*). Reports indicate that autonomous-ready heavy-haul mine trucks are being utilized and considered by several mining companies in the Canadian oil sands region (see Figure 10). These companies are looking for ways to cuts costs and boost productivity (*48*).

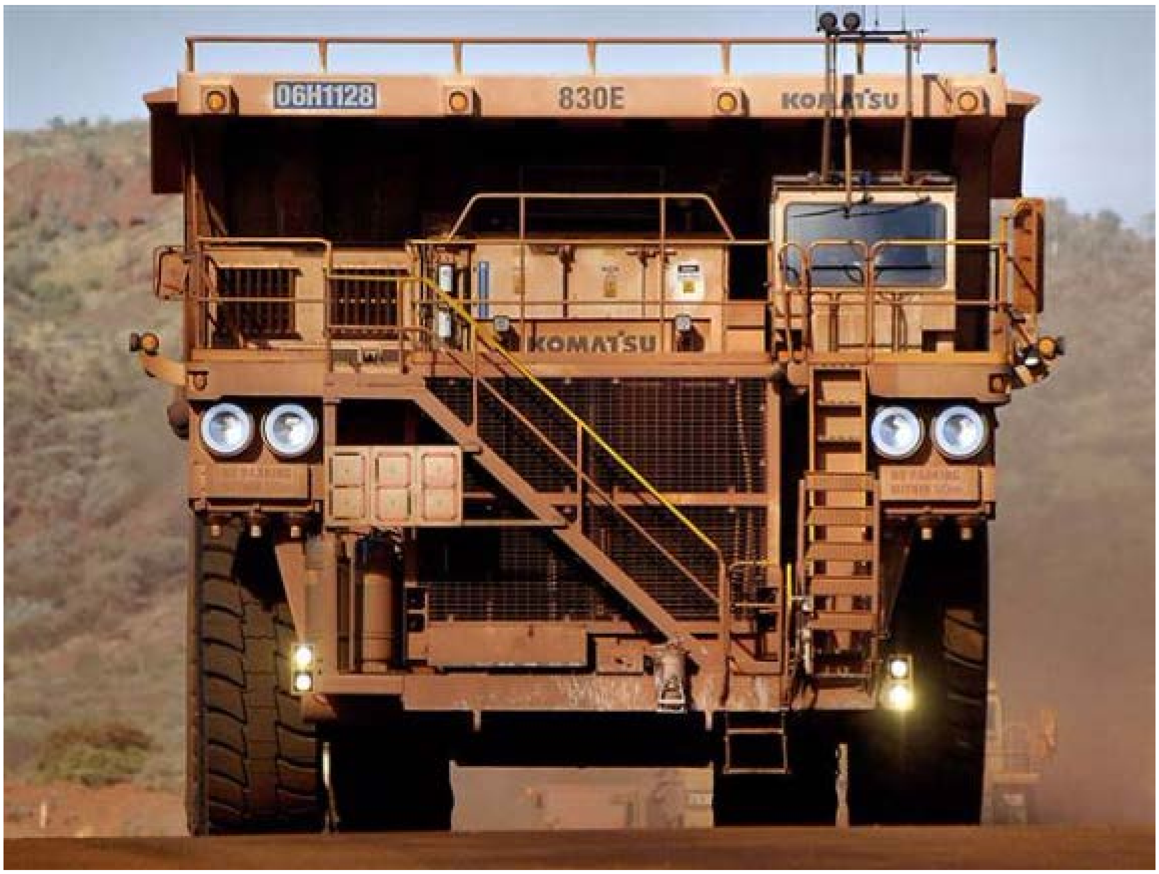


Figure 10. Heavy Autonomous-Ready Mining Truck (*48*).

Agriculture has seen dramatic increases in yields as technology has been incorporated into the industry. GPS and similar technologies allow farmers to more precisely maximize land use and product collection. Automation is now contributing to the agriculture industry. A paper on self-driving vehicles in logistics by the Germany-based global logistics company DHL includes an example of a German manufacturer of agricultural tractors that has launched a system that connects two tractors via satellite navigation and radio communication to form one unit. It states that one of the two vehicles is unmanned and performs the same working procedure as the manned vehicle, such as turning together at the end of a field (*47*). Benefits include improved productivity, reduced labor costs, and improved efficiency of operations.

Warehousing Functions

Warehouses are another area where technology advancements are increasing productivity. This productivity is required to handle the increasing number of e-commerce–generated shipments. Largely, up to this point, warehouses have been used to combine large shipments to retail establishments where customers purchased the goods. The ability for customers to purchase items online to be delivered to their doors has increased the number of small individual orders that have to be handled in warehouses in preparation for direct home delivery.

Automation within warehouses includes autonomous loading and unloading, autonomous transport of products through the warehouse, and automated order fulfillment. Figure 11 displays how a warehouse may operate with advanced communication and automation technologies.

Figure 11. Graphic Demonstrating Advanced Communication and Automated Warehouse Technology (*47*).

A recent global trend is the growing size of the major distribution warehouses. Without the increased productivity produced by the advanced warehouse technologies, it would be difficult to efficiently and cost-effectively handle the goods within these giant distribution centers. This trend is toward distribution facilities consisting of floor spaces larger than 1 million square feet. Colliers reports that before 2011, only one of 10 Amazon freight centers in Europe was larger than 969,000 square feet. Now 10 out of 27 Amazon distribution centers exceed that floor space threshold (*42*).

Terminals

Automation in major container terminals is not new. The first container port terminal incorporating automation was the Rotterdam, the Netherlands, ECT Delta Terminal in 1993 (*49*). Now there are more than 500 driverless cranes in operation worldwide at some 20 automated terminals, with more than 10 major new automation projects being executed around the world. The main benefits of utilizing automated cranes are improved reliability, predictability, and safety of operations; reduced environmental impact; and better land utilization.

The automated cranes are used to stack containers for storage, either as they come off a ship or while waiting to go on a ship. Additionally, terminals are utilizing driverless drayage tractors to transport containers between the ship and storage area. DHL identifies the Harbor Container Terminal Altenwerder in Germany as one of the most advanced handling facilities in the world. Container handling is almost completely automated, with the use of a total of 84 driverless vehicles that transport containers between the wharf and the storage areas via the fastest possible routes (*47*). Figure 12 provides an image of one of the Altenwerder driverless vehicles.

Figure 12. Autonomous Container Port Drayage Vehicle (*47*).

In addition to autonomous container transporters, autonomous unit loading devices are being considered in air cargo operations to assist with loading and unloading of specialized cargo units designed to fit in air cargo aircraft.

Line Haul

Up to this point in the supply chain process, automation is largely being used in closed environments. The existing and continued development of AV/CV technologies for the line-haul portion of the process causes the technology to operate within the public environment.

Autonomous Truck Operations and Truck Platooning

As discussed in Chapter 2, the levels of automation range from no automation (Level 0) to full self-driving automation (Level 4). While some of the examples listed in the warehouse and port terminal environments are Level 4, the automation of trucks on highways is not to that level but could be fast approaching it. Existing AV/CV technologies on trucks, several of which are discussed in more detail later in this section, assist drivers by providing information about vehicles located in blind spots or safe driving distances, or even by applying emergency braking. Current testing of more advanced automation technology will soon enable the truck drivers to cede full control of the driving function to the vehicle. These technologies will reduce the driving tasks by taking control of the standard line-haul portion of the trip. These technologies will help reduce crashes, save fuel, and improve the driver workload.

One opportunity to expand the benefits of AV/CV technologies from one truck to multiple trucks is the concept of truck platooning. This practice will use AV/CV applications to allow two or more trucks to follow each other closely. The likely first scenario of truck platooning involves the driver of the first truck retaining control of all steering functions and setting the pace. The following trucks would operate in communication with the first truck and would not require the truck drivers to actively participate. Future scenarios could include the lack of need for drivers to be in the following truck and/or the lead truck during the line-haul portion operating without driver control.

In addition to the potential safety benefits of autonomous truck operations and truck platooning is the potential improvement in truck fuel economy. Figure 13 demonstrates how truck platoons lower fuel usage. By traveling in the aerodynamic draft of the front vehicle, the rear truck will use an estimated 10 percent less fuel, and the combined fuel savings between both trucks is estimated at 7 percent at 65 mph (*50*).

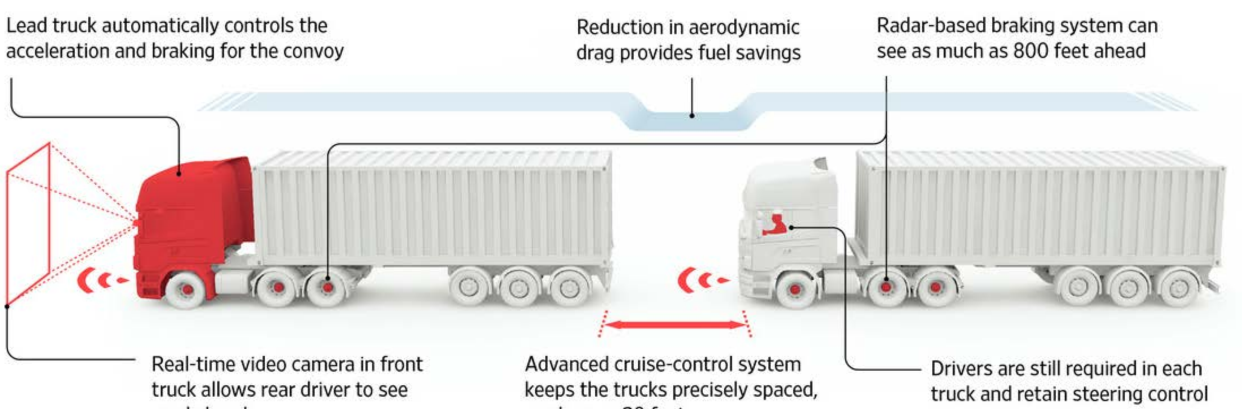


Figure 13. Illustration of How Truck Platooning Lowers Fuel Usage (*50*).

Safety Impacts of Line-Haul Truck Operations Automated and connected vehicle technologies promise numerous benefits to commercial truck operations by dramatically improving the hazard information available to the drivers and/or controlling vehicle operations in a safe manner. Some technologies are already in use by operators, such as forward collision warning or mitigation systems (FCWSs) and blind-spot warning (BSW) systems. An ITS America report estimated trends in adoption of a suite of advanced safety technologies among large fleets of 300 vehicles or more and 50 percent or more tractors. Based on the study survey and estimates, the authors concluded that companies that have deployed any combination of lane departure warning or mitigation systems (LDWSs), ESCs, FCWSs, BSWs, and vehicle communication systems (VCSs) report significant safety improvements. The main reasons for deploying these technologies include reduced cost of crashes, an improved safety culture, proven safety benefits, and, to a lesser extent, reduced insurance premiums. It was estimated by the study survey respondents that LDWSs reduced crashes by 14 percent, ESCs by 19 percent, FCWSs by 14 percent, BSWs by 5 percent, and VCSs by 9 percent (*51*).

Following are descriptions of some of the vehicle-to-vehicle and vehicle-to-infrastructure applications.

- **Intersection Movement Assist (IMA)—**The IMA application on a commercial vehicle gives the driver a warning only when the accelerator is pushed and the vehicle speed begins to increase, in order to stop the truck from entering an intersection with another vehicle approaching (*52*). Additionally, the estimated acceleration capability of a commercial vehicle is less than that of a light vehicle, so the commercial vehicle parameters allow a longer driver response time. Therefore, this application can provide collision warning information to the vehicle operational systems to reduce the possibility of crashes at the intersection (*53*).
- **Forward Collision Warning or Mitigation Systems—**The concept of an FCWS is derived from the scenario in which a truck is following a light-duty vehicle. ZF TRW has divided FCWSs into two categories: camera-based and radar-based. A forward-looking monocular camera with object recognition will be used for the camera-based FCWS deployment. The radar-based FCWS will be performed by a 24 GHz medium-range radar sensor, which provides highly reliable data by measuring distance and relative speed directly in any weather conditions (*54*). As mentioned above, a commercial vehicle cannot brake as well as a light vehicle. Thus, the implementation of this technology is expected to help drivers avoid collision by warning them with sound and light signals when they approach too close to the front vehicle (*55*). Figure 14 demonstrates the FCWS application.

Figure 14. The Concept of an FCWS (*52*).

- **Emergency Electronic Brake Light (EEBL)—**The EEBL application applies to a suddenly slowing vehicle ahead of the truck. The concept of this application is very similar to the FCWS. However, the EEBL application is more sensitive to vehicles farther ahead. If the slowing vehicle is in the same lane as the truck, the application delivers a warning to the driver with an audible sound but less intensive than the FCWS application. On the other hand, if the slowing vehicle is ahead but in a different lane, the EEBL delivers only a silent alert. This application deals with any sudden lead vehicle deceleration that exceeds a preset threshold as a potential threat to the truck (*52*).
- **Blind-Spot Warning and Lane Change Warning (LCW)—**The BSW application gives drivers an alert when another vehicle enters the blind zone on either side of the commercial vehicle. According to a Federal Highway Administration (FHWA) report, the silent BSW message switches to an audible BSW+LCW warning sound when the truck driver begins to signal a lane change toward the light vehicle. Figure 15 demonstrates the simulation scenario of a BSW and LCW. Unlike with a light vehicle, a commercial vehicle has a different blind-spot size and position based on the fleet size or trailer configuration. Thus, the BSW application on a commercial vehicle is designed to cover all the areas up to the left side of the driver and extend beyond the front of the vehicle on the right side (*52*).

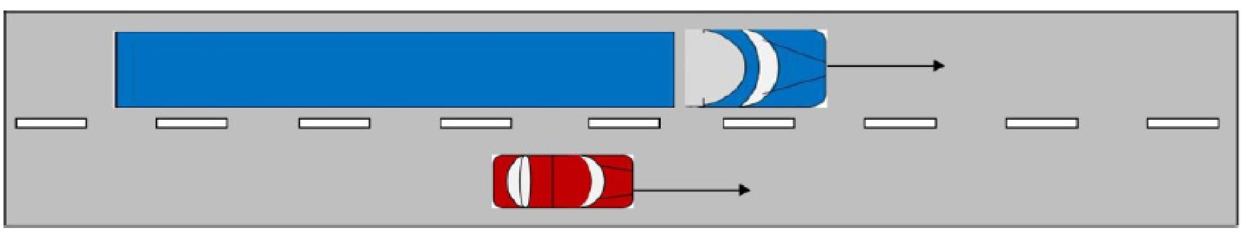


Figure 15. The Simulation Scenario of BSW+LCW.

- **Bridge Height Inform (BHI)—**The BHI application is one of the vehicle-to-infrastructure technologies. This system warns drivers in advance of a low-clearance bridge or overpass as a stationary advisory sign on the road (*52*).
- **Curve Speed Warning (CSW)—**The CSW compares the advisory speed for a curve with the current speed of the truck and warns the driver to slow when the advisory

speed is exceeded on approach. This application is advantageous over a conventional speed advisory sign in that it accounts for the truck's actual speed and it can include an audible component (*52*).

Autonomous Freight Systems

Many of the challenges facing freight, such as roadway congestion and driver shortages, have led to investigations into innovative alternative freight transportation concepts. Investigations into the use of such systems generally revolve around the transport of containers from container port facilities to inland distribution points to bypass congested and inadequate roadway infrastructure, cross congested border crossings, and bypass congested freight roadway corridors. These autonomous systems operating in their own right of way look to provide a high-volume solution to freight movement along designated routes. National Cooperative Freight Research Program (NCFRP) Report 34 summarizes favorable conditions for automated, fixed-guideway systems for landside transport of containers as follows (*56*):

- Single multiuser or clustered terminals.
- High terminal automation.
- Single land point.
- New or clear right-of-way context.
- Multiple terminal shifts (24/7).
- Less demand peaking.
- Medium distance (100–500 mi).

One example of the technology under development is the Freight Shuttle System by the Texas A&M Transportation Institute. As shown in Figure 16, the Freight Shuttle System has recently moved from concept into prototyping and consists of independent autonomous truck-like container vehicles operating on a dedicated, grade-separated guideway.

Figure 16. The Freight Shuttle System Transporting a Trailer.

Last-Mile Delivery

The last-mile delivery is often the least predictable and most expensive portion of the supply chain. AV/CV technology could play a role in improving the efficiency of last-mile deliveries. One last-mile delivery application is in support of letter or package deliveries where the driver is often walking outside the truck. Instead of the driver returning all the way back to the truck, the truck could advance autonomously to a more effective location for the next delivery (*47*). Another application could be autonomous parcel repositories where packages would be within lockers on an autonomous vehicle. The vehicle would travel at a designated time to a location closer to the package customers, stay for a set amount of time, and allow the customers to pick up their packages at a more convenient location. As discussed in Chapter 3, shared autonomous cars could be summoned for personal transport. They could also be utilized in the shipment of cargo items.

One highly publicized form of last-mile delivery is the use of unmanned aerial vehicles (UAVs) to transport packages in urban areas, as depicted in Figure 17. Companies such as Amazon, DHL, and Google are actively working to develop UAV concepts to use for last-mile freight delivery. As previously discussed, the development of smaller urban warehouses locates the warehouse closer to the customer, making the use of UAVs more viable given potential range concerns for the technology. Swiss Post Ltd., Switzerland’s postal service; Swiss WorldCargo, the air freight division of Swiss International Air Lines AG; and California-based drone manufacturer Matternet are testing the use of drones in logistics. The drones are expected to cover several types of delivery, such as delivery to peripheral areas, for the fast or expedited delivery of goods (*57*). Also, UAVs could be paired with traditional delivery trucks, especially if the warehouse is located farther away from the customer, to act as an assistant to the driver. In this scenario, as the driver makes deliveries, the UAV is launched from the truck, carrying parcels for individual customers. The UAV would then return to the truck, which has moved to a new customer location (*58*).

Figure 17. A UAV Transporting a Package (*59*).

TRANSIT AV/CV SYSTEMS

Commercial vehicles also include transit vehicles that commercially transport people. Transit signal priority (TSP), or bus signal priority (BSP), has been used for over 20 years to improve the safety and efficiency of transit operations. TSP/BSP systems are operated with a hardware device installed on a bus to communicate mutually at the intersection. In this case, the green duration can be extended for the approaching vehicle to pass through the intersection without stopping (*59*). Thereby, the systems are expected to reduce the delay at intersections, save travel time, and increase the transit service quality. According to a report from the University of Virginia, the TSP system has adverse effects on side streets, and it is difficult to predict the exact arrival time of buses due to the extended green signal. To address these shortcomings, the university's research team developed "Advanced TSP," also known as intelligent TSP, with the collaboration of CV technology. The improved system was implemented in the Northern Virginia area and is expected to improve travel time efficiency for buses (*60*).

In Zhengzhou, China, bus manufacturing company Yutong implemented a self-driving bus that has a maximum speed of 42 mph. The company developed a system for the driverless bus to include two cameras, four laser radars, and an integrated navigation system. The bus successfully performed "a series of highly complex driving acts," such as lane changing, overtaking, and responding to lights (*61*).

As a type of automated guideway transit, personal rapid transit (PRT), also known as podcar, is a system of driverless taxicabs that can take passengers to their destinations along dedicated routes without stopping midway. On the West Virginia University campus, the only PRT in the United States has been operating since 1975 and carries approximately 15,000 riders per day during the school year (see Figure 18) (*62*). Also, the first self-driving electric shuttle, WEpod, is planned to be implemented in the Netherlands. It has been tested in Finland on a fixed route, but the routes and regions are expected to expand in early 2016. The WEpod will be equipped with cameras, radar, laser, and GPS to track the vehicle (*63*).

Figure 18. The Personal Rapid Transit System at West Virginia University.

CONCLUSION

Drawing conclusions regarding the expected impacts of AV/CV implementation on planning remains a difficult task. The freight and commercial sector in Texas faces a number of forecast changes, such as a rapidly growing population and a resulting escalating amount of daily freight trips in the coming decades. These impacts will be felt most within Texas's urbanized areas and near special freight generators/intermodal sites where freight traffic is greatest. At the same time, automation of freight movement processes and improved planning data promise to revolutionize how freight is delivered and routed between producers and customers through distribution centers, warehouses, and direct door-to-door delivery.

As AV/CV systems are advanced and put in place on the state's transportation network, there is a likelihood that freight-related transportation-sector stakeholders will adopt and implement AV/CV technology more rapidly than private individuals will for personal vehicles. During this transitional period and as AV/CV systems become more widely adopted, truck freight innovations such as platooning or truck automation on and around special freight generators may become commonplace. Once a full transition to AV/CV has occurred, planners will need to ensure that the massive numbers of automobiles on the system do not fail to account for differing operating characteristics and needs of heavy trucks and other freight vehicles.

Several questions remain unanswered regarding planning impacts of commercial and freight vehicles becoming more automated and connected. In an AV/CV environment, and in the transition to fully automated roadway operations, these include the following:

- How will commercial/freight vehicles and their exceptional (i.e., differing) operating characteristics be accounted for in traffic flows of mostly heterogeneous passenger vehicles (i.e., how will freight vehicle operational needs be accounted for in traffic streams made up largely of small standardized passenger pods)?
- To what degree and how soon will commercial trucks also be automated, and on what schedule in relation to other vehicles? What role will government entities play in determining this schedule?
- Will platoons of trucks have single drivers or will each trailing truck have an alert driver on standby for decoupling upon entering urban or congested areas? Will special facilities be needed upon entering urban areas to decouple platooned vehicles? How often will the lead truck need to switch for maximum safety?
- Will the required leading braking/stopping distance for heavy vehicles be accommodated by the AV/CV system? Will personal AV/CVs be restricted from entering or changing lanes into such a braking area in traffic flow? How will safe separation be maintained?
- What are the safety and operational impacts to operation of commercial trucks in mixed traffic versus operation in dedicated freight-only lanes within an AV/CV system? Would these impacts require separated facilities or merely adjacent, designated lanes?
- What impacts could AV/CV technologies have on reducing congestion at and nearby freight facilities such as airports, rail intermodal yards, pipeline terminals, and seaports?
- What types of infrastructure changes may be necessitated to accommodate AV/CV technology for commercial vehicles (i.e., longer or reconfigured transition lanes/merge areas, exit designs)?

CHAPTER 5. POTENTIAL AUTOMATED/CONNECTED VEHICLE IMPACTS TOTRAVEL FORECASTING

INTRODUCTION

Estimating the potential impacts associated with the adoption and implementation of autonomous vehicles involves a great deal of uncertainty. It may be possible, through the use of behavioral preference surveys, to estimate travel parameters based on stated activities that users would elect to do given a level of understanding of the technology. However, in the absence of this type of data collection, modeling the influence of AV/CV technologies on trip making, modes, and routes will be limited. Presupposed conditional criteria could range from radical speculation to conservative thinking or a combination of the two. The potential impact on travel and land use could be significant enough to constitute a seismic shift in how society views and reacts to travel (*64*). As such, for this research study, researchers examined the potential automated/connected vehicle impacts to the Texas travel forecasting (Task 4). The research team adopted the following approach for this task:

- Define the problem.
- Identify a study area model to use.
- Determine reasonable scenarios.
- Test scenarios that metropolitan planning organizations (MPOs) throughout the state could easily adopt.
- Measure the results.

Defining the Problem

For this research study, researchers assumed that 100 percent of the vehicle mix would reflect a fully integrated self-driving automated system. This assumption is consistent with the NHTSA automated vehicle Level 4 definition (*4*). A number of research reports attempt to document the anticipated adoption of different enabling technologies and fleet turnover. For this study, the entire driving fleet was assumed to be fully autonomous and connected. Within different scenarios tested, households would maintain current vehicle ownership levels (and activities) but drivers would relinquish navigation to the automated vehicle or would participate (albeit limited) in greater shared-ride alternatives. The vision of greater shared rides and travel tours is sometimes referred to as robo-taxis or shared autonomous vehicles. Although it is easy to envision a system of greater shared vehicle use, it is difficult to predict the degree of acceptance of shared rides within individual tours of travel. Therefore, shared-ride usage in the modeling in this study was held constant or proportionally adjusted based on existing forecast mode shares.

Identifying a Study Area Model

The Texas Department of Transportation's Transportation Planning and Programming Division (TxDOT-TPP) develops and maintains travel demand models (TDMs) for the remaining

21 urban areas in the state. The exceptions are Dallas–Fort Worth (North Central Texas Council of Governments), Houston-Galveston Area Council (H-GAC), Capital Area Metropolitan Planning Organization (CAMPO), and San Antonio Metropolitan Planning Organization urbanized areas. The models are developed on five- to 10-year planning update cycles, which are consistent with the five-year saturation traffic count data collection program and the 10-year travel survey program in the state. Both programs are administered and supported by TxDOT-TPP.

For 24 of the 25 metropolitan planning organization models in the state of Texas, a trip-based travel demand model is used. Only one MPO in the state has implemented an activity-based model (ABM)—the Houston-Galveston Area Council of Governments. Outside of the other largest metropolitan areas in the state (i.e., Dallas–Fort Worth [DFW], Austin, San Antonio, and El Paso), the remaining trip-based models are daily three-step models involving direct generation, distribution, and assignment of vehicle trips. DFW, Austin, San Antonio, and Houston have calibrated mode choice models. The El Paso travel demand model has a mode *share* step that converts person trips to vehicle trips and estimates transit mode shares, but this step does not involve direct transit trip table estimation and assignment.

For the purposes of experimentation in this study, researchers selected the 2040 travel demand forecast application developed by CAMPO as the travel demand model application. Unlike a majority of the small- to medium-sized study area travel models under the developmental purview of TxDOT-TPP, the Austin area experiences extreme congestion and contains a mode choice component in the sequential travel demand model architecture. The Austin metropolitan area currently ranks as the 10th most congested city in the United States based on TTI's Annual Mobility Report (*65*). The small- to medium-sized urbanized areas throughout the state experience limited appreciable levels of system-wide congestion beyond narrow peak periods or spot congestion. The models developed by TxDOT-TPP do not currently contain a mode choice component, simply because transit ridership numbers are so low in many of these urbanized areas. Enumerating system or demand changes associated with AV/CV implementation, although possible, probably will not convey the full magnitude and influence that this technology might have in a less-congested study area. Therefore, the more congested region was selected.

Brief Summary of the CAMPO Travel Demand Model

The 2010–2040 CAMPO travel demand model is a sequential four-step, trip-based travel model that covers six entire counties in central Texas—Bastrop, Burnet, Caldwell, Hays, Travis, and Williamson. Figure 19 illustrates the location and size of the six-county region relative to the state of Texas.

Figure 19. Location of CAMPO Study Area.

Figure 20 provides a more detailed illustration of the six-county area relative to the major roadway network in the region.

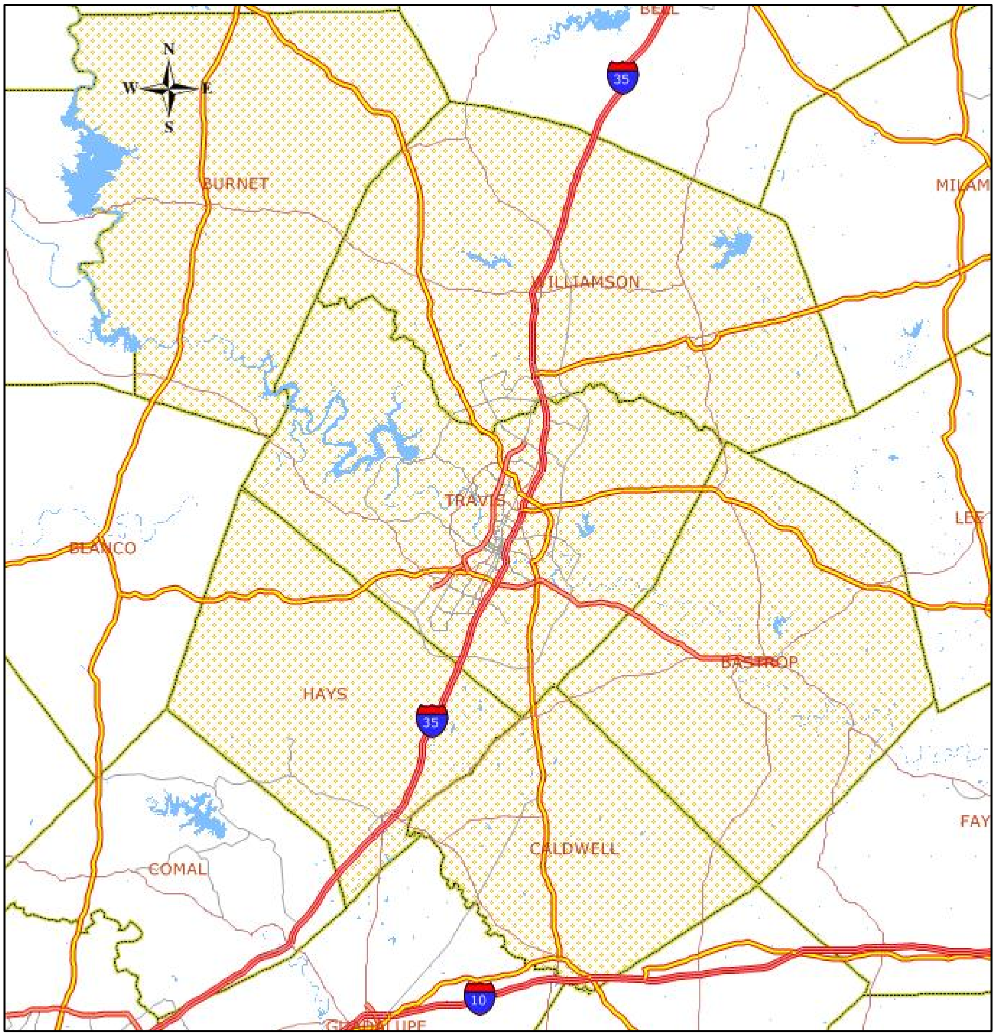


Figure 20. Detailed Image of Six-County CAMPO Model Area.

According to the latest population figures from the Texas State Data Center (TSDC), the six-county population total in the Austin metropolitan area is projected to grow by more than 64 percent to nearly 2.8 million people (*66*). This is an increase of 1.1 million people in the area during the 30-year period between the 2010 base and the 2040 forecast application. Table 8 shows the latest population figures from TSDC by county for the region.

Table 8. Population Trends for Six-County Austin Metropolitan Area.

County	Total Population 2010	Total Population 2040	Total Pop Growth 2010 to 2040	Total % Growth 2010 to 2040	% of Total Growth 2010 to 2040
Bastrop	74,171	125,914	51,743	69.76%	4.59%
Burnet	42,750	56,473	13,723	32.10%	1.22%
Caldwell	38,066	57,444	19,378	50.91%	1.72%
Hays	157,107	346,625	189,518	120.63%	16.81%
Travis	1,024,266	1,474,822	450,556	43.99%	39.97%
Williamson	422,679	825,127	402,448	95.21%	35.70%
Region	**1,759,039**	**2,886,405**	**1,127,366**	**64.09%**	

Source: (*66*).

Travis County is projected to receive the largest aggregate growth of the six counties. Williamson County, which is just north of Travis County, is a fast-growing suburban community that is expected to nearly double during the 30-year period. Hays County, the neighboring county south of Travis, is also a fast-growing suburban community in the region and is expected to more than double in size in terms of total population. Figure 21 illustrates the changes in 2010 and 2040 total population by county in the region.

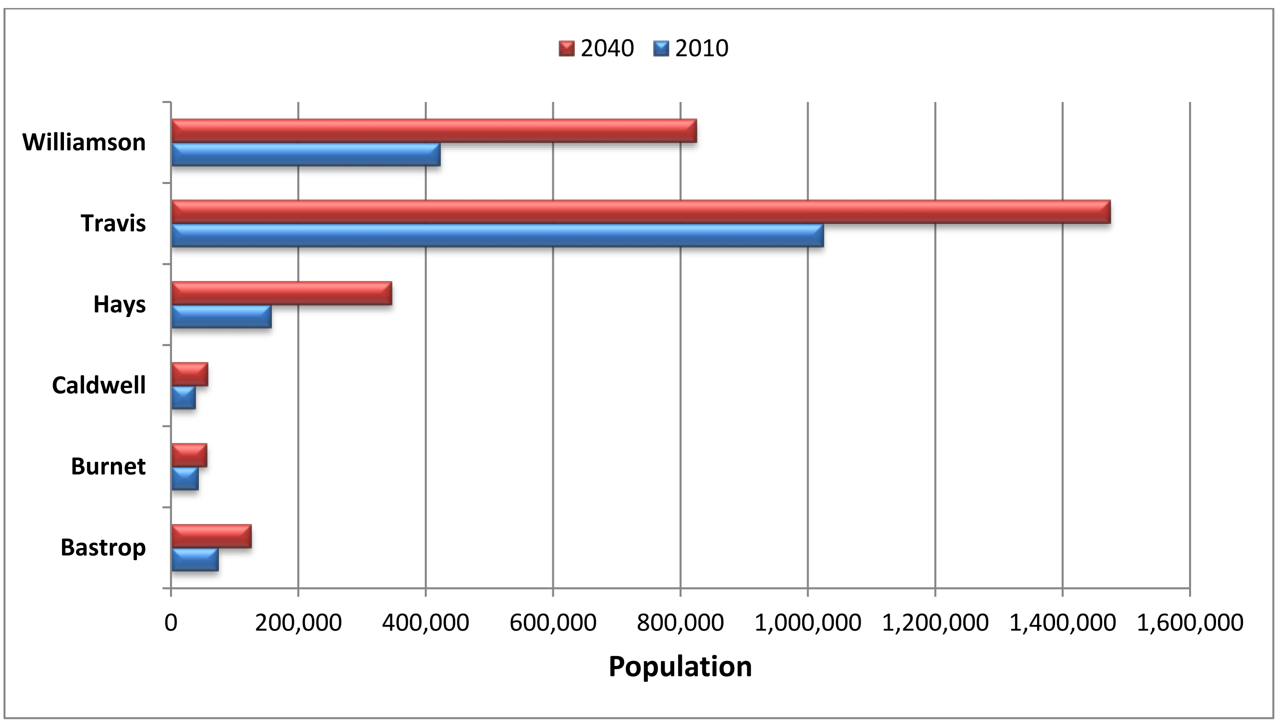


Figure 21. Austin, Texas, Six-County Population Projection (2010–2040).

The 2010 travel model represents a validation of the previous 2005 base-year model. This model used the 2005–2006 household, workplace, commercial vehicle, special generator, external station, and onboard Capital Metropolitan Transit Authority (CapMETRO) travel survey data. The 2010 travel model is augmented by the availability of a more recent onboard transit survey.

There are 2,102 internal traffic analysis zones (TAZs) and 59 external stations in the CAMPO travel demand model. There are also 97 dummy zones, which can be utilized to split existing zones during future alternative analyses. In the network geography, there are 25 distinct facility types, including centroid connectors. The calibrated per-lane per-hour capacities are listed in Appendix D. The period capacities are derived by multiplying the product of the per-lane facility type capacity by the number of lanes on each link by the peak-period factor. Table 9 lists the four time periods and period factors.

Table 9. CAMPO TDM Time Periods and Capacity Factors.

Period	**Hours**	**Factor**
AM	6 a.m. to 9 a.m. (3 hours)	2.795
Midday	9 a.m. to 3:30 p.m. (6.6 hours)	5.750
PM	3:30 p.m. to 6:30 p.m. (3 hours)	3.000
Overnight	6:30 p.m. to 6 a.m. (11.5 hours)	5.200

Nearly 3,700 of the 13,581 non-centroid connector links are annotated with either a 2010 annual or urban saturation county (*67*).

The transit network consists of six modes—local bus, express bus, University of Texas bus, commuter rail, and two premium rails reserved for future alternatives.

The CAMPO travel demand models use daily generation and distribution of person trips prior to mode choice. After mode choice, the daily trip tables are segmented into four distinct time periods. An iterative feedback technique is used to resolve travel times within the sequential trip-based models. Figure 22 depicts the general modeling steps in the existing 2010–2040 CAMPO travel demand model.

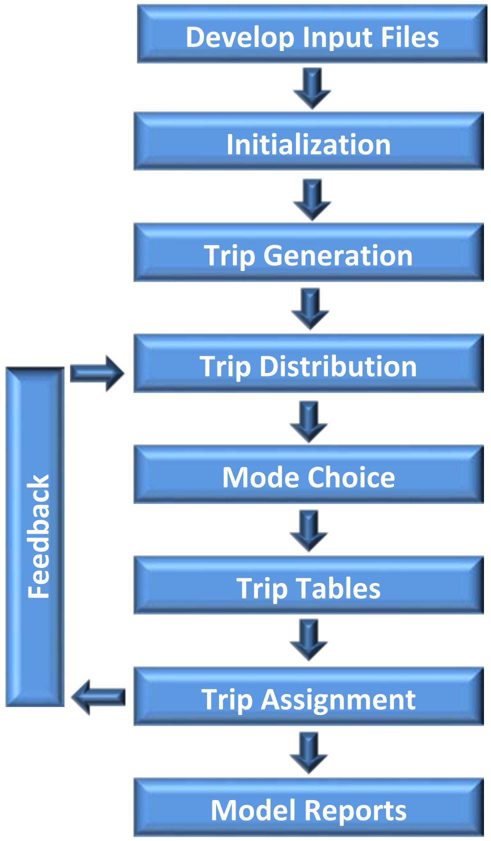


Figure 22. CAMPO Travel Demand Model Application Diagram (*67*).

There are 15 trip purposes in the 2010–2040 CAMPO TDM. These are:

- Home Based Work (HBW).
- Home Based Non-Work—Retail (HBNW-R).
- Home Based Non-Work—Other (HBNW-O).
- Non-Home Based Work (NHBW).
- Non-Home Based Other (NHBO).
- Primary Education (ED1).
- Secondary Education (ED2).
- University of Texas (UT).
- Airport (AIR).
- Truck-Taxi (TR-TX).
- Non-Home Based—External (NHB-EX).
- External-Local—Auto (EXLO_A).
- External-Local—Truck (EXLO_T).
- External-Thru—Auto (THRU_A).
- External-Thru—Truck (THRU_T).

Zonal productions are derived using trip rates cross-classified by household size, household income, and workers per household. Zonal attractions are determined using a cross-classification of rates by area type and employment category by trip purpose. There are five area types (central business district [CBD], urban intense, urban residential, suburban, and rural) and five employment categories (basic, retail, service, primary education, and secondary education), with exceptions for UT and airport trip ends.

The CAMPO trip distribution step is a gravity analogy that uses composite travel times as input. Composite travel time is the sum of free-flow travel time (congested travel time during the feedback process) and generalized costs of toll and operating costs converted to time. Appendix E lists the free-flow speeds by facility type.

The CAMPO mode choice model uses a nested logit structure with three primary segments (auto, transit, and non-motorized). Resulting auto-trip tables, post mode choice, are assigned to the network using a generalized cost multimodal multiclass (MMA) bi-conjugate Frank-Wolfe (BFW) user equilibrium approach. The four individual periods can be summed into daily trips. The vehicle trip tables are segregated into two general categories—autos and trucks—but can be further distinguished by trip purpose.

Defining AV/CV Scenarios

Figure 23 illustrates the potential number of items that could be given consideration using a typical (trip-based) travel model in the context of AV/CV scenario planning. Each of the considerations in the figure could go in any number of directions when attempting to predict potential reactions and counteractions toward full adoption of autonomous and connected vehicles.

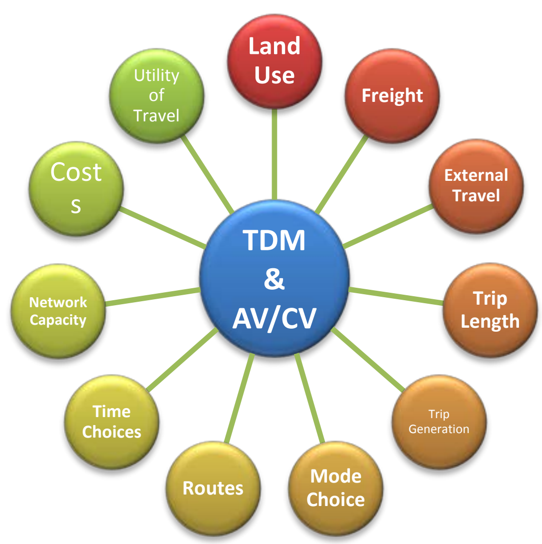


Figure 23. Potential Issues to Consider When Addressing AV/CVs.

A number of outcomes could result given that relevant and measured data simply do not exist on how each of these variables could impact travel behavior relative to wide-scale adoption of AV/CVs. As one example, Figure 24 illustrates additional considerations that could be studied as potential outcomes associated with the land use inputs in a future AV/CV scenario analysis. In this example, greater dispersion of household and workplace locations could occur because of improved travel times. Ease of travel might encourage households to locate farther away from workplace settings. Retail locational criteria could also change relative to an evolving marketplace. Paradoxically, land use and urban form could be potential examples of the unintended consequences associated with the potentially transformative nature of AV/CV technology. As transportation safety and reliability increase, and travel times (rather, disutility to travel) decline, the need for concentrated city activity centers may also decline. As stresses to transportation infrastructure decline, other city services (e.g., utility and city services) may increase as people move farther away from highly urbanized areas.

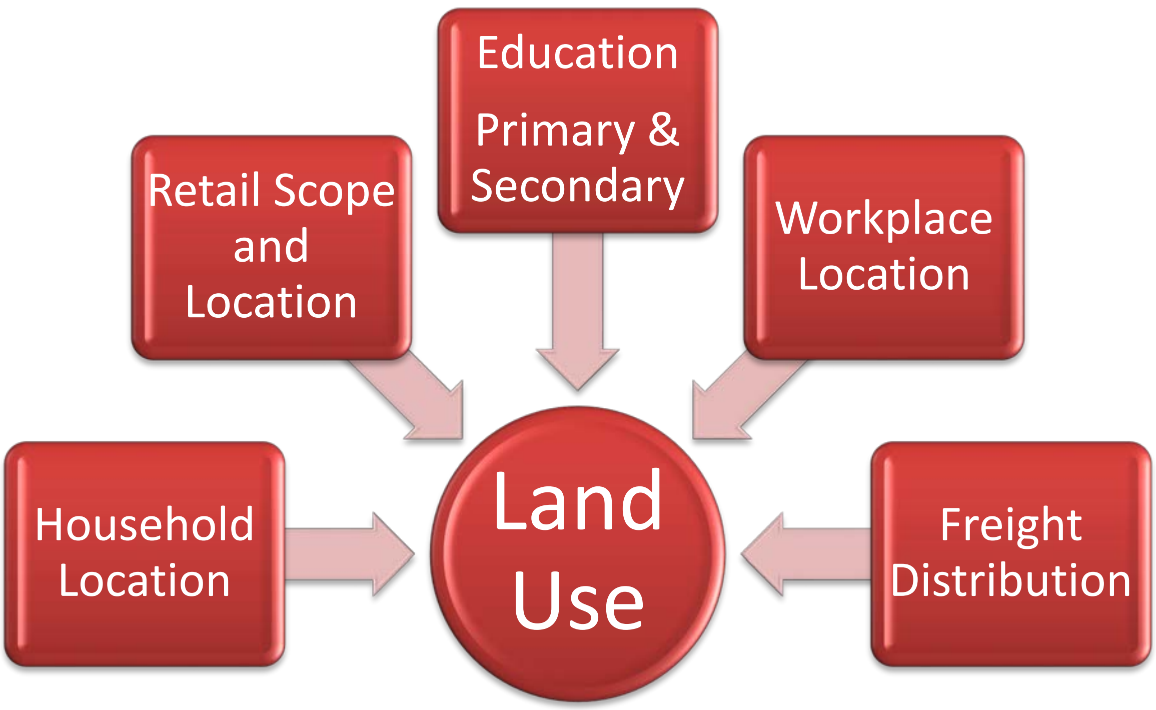


Figure 24. Potential Land Use Considerations.

Because of the degree of uncertainty and variance in each model input, researchers undertook a simple incremental approach for the initial analysis. This approach is similar to the one taken by the Atlanta Regional Council (*68*). Rather than trying to address multiple topics simultaneously, the study design focused on incrementally evaluating the impacts of certain changes on vehicle miles of travel (VMT), vehicle hours of travel (VHT), delay, and modes. Table 10 defines the six scenarios evaluated as part of the study.

Table 10. Scenarios Studied.

Base	Scenarios					
	S1	**S2**	**S3**	**S4**	**S5**	**S6**
2040 MTP Forecast	Limited increase in EXPWY and FRWY capacity	Limited increase in EXPWY and FRWY capacity	Limited increase in EXPWY and FRWY capacity	Limited increase in EXPWY and FRWY capacity	Limited increase in EXPWY and FRWY capacity	Limited increase in EXPWY and FRWY capacity
		Increase per-hour per-lane capacity of FRWY links	Increase per-hour per-lane capacity of FRWY links	Increase per-hour per-lane capacity of FRWY links	Increase per-hour per-lane capacity of FRWY links	Increase per-hour per-lane capacity of FRWY links
			Increase arterial capacity by 10%	Increase arterial capacity by 10%	Increase arterial capacity by 10%	Increase arterial capacity by 10%
				Proportionally move transit trips to SOV and HOV (2 and 3+) trip tables	Proportionally move transit trips to SOV-only trip table	Proportionally move transit trips to HOV trip tables

Note: MTP = metropolitan transportation plan; SOV = single-occupancy vehicle; HOV = high-occupancy vehicle.

The definitions of the base and six scenarios are as follows:

- **Base—**CAMPO's existing 2040 forecast application. This model is the financially constrained long-range planning model that is consistent with the current MTP.
- **S1—**Edit the CAMPO 2040 network geography by adding a lane to each direction for expressway functional classes and above. This scenario represents the retirement of one directional emergency lane since two emergency lanes may no longer be necessary in a fully automated system that improves vehicle flow and corresponding safety. Alternatively, this scenario could be thought of as narrowing of lanes that allows for an additional direction lane.
- **S2—**Utilize the Scenario 1 network geography and increase the per-lane per-hour capacity for freeway functional classes to 4,000 vehicles per hour per lane. The network capacities tested in Scenario 2 conceptually might be achieved if weaving, ramp metering, and gaps between vehicles are reduced. This scenario does not represent a doubling of per-lane capacities but is an aggressive increase in freeway per-lane capacities.

- **S3**—Utilize the Scenario 2 network geography and increase the per-lane per-hour capacity for arterials by 10 percent. The per-lane per-hour capacity of the arterial roadway network increase was minimized relative to the freeway concept used in Scenario 2 because there are limits to how much traffic can be improved at intersections with existing technologies. This scenario does acknowledge that there will be some benefits to the signal controlled system.
- **S4**—Utilize the Scenario 3 network geography and proportionally move the transit trips to SOV and HOV 2 and 3+ trip tables. This was manually accomplished post mode choice and is meant to represent a future scenario without fixed transit.
- **S5**—Utilize the Scenario 3 network geography and move all transit trips to SOV-only trip tables. This was manually accomplished post mode choice and is meant to determine the level of impact of converting all transit trips to non-shared-ride autos. This conceptually could occur if technology makes owning and operating fixed transit less competitive to either shared autonomous vehicles or individually owned autonomous vehicles. This scenario also replaces on-demand transit services with on-demand vehicle service.
- **S6**—Utilize the Scenario 3 network geography and move all transit trips to HOV trip tables. This was manually accomplished post mode choice and is meant to determine the impact of converting all transit trips to shared-ride auto trips (e.g., robo-taxis).

Each of the scenarios listed above was applied to the AM period. The four time periods were not summed to daily results. The AM period was chosen because of the peak travel characteristics and congestion levels. A seventh scenario was also applied. Specifically, researchers applied an all-or-nothing (AON) assignment, which removed capacity as a constraint. This alternative was selected to determine if any of the previous six scenarios would approach the traffic patterns evident in the AON assignment results.

Assumptions

Because of the uncertain nature of change and lack of observed data, a majority of the model inputs were held constant for this study. The study focused on the two components that could be tested by multiple MPOs in the state—network capacities and mode shares. Three primary components could be tested in the CAMPO model related to AV/CV trip generation, network capacities, and mode shares. Other issues of AV/CV modeling would require adopting some new approaches (e.g., traffic assignment models that could not be calibrated).

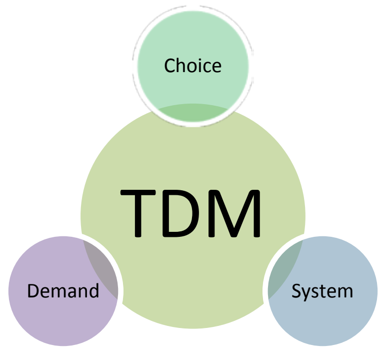


Figure 25. Scenario Options.

For each of the six scenarios previously described, the existing trip rates and trip lengths were presumed to be consistent with the existing 2010–2040 CAMPO travel demand models. However, cogent arguments could be made to modify these variables. Evidence from travel surveys of individuals using AV/CV technology still does not exist. Therefore, testing different household production and workplace attractions was not deemed appropriate at this time.

Similarly, the existing 2040 forecast demographic scenario was held constant for this exercise. Researchers did not test different household and workplace locations because of the uncertain nature regarding market reactions of household and workplace location choice if travel times and accessibility improve because of AV/CVs. Businesses may rethink their location, depending on the importance of accessibility to other services or markets and the business objective. There could also be a number of future policy changes aimed at addressing future land use patterns, and land use reactions may become more evident. Scenarios regarding land use changes were not part of this exercise.

The scenarios also presumed that existing auto ownership models would remain unchanged. Therefore, for these applications, households would still own automobiles at current market penetration rates but would relinquish navigation and other driver control to onboard technologies. However, Scenario 6 examined the effect of converting all existing transit trips to shared-ride automobile trips (e.g., robo-taxis), which infers a change in auto ownership levels. This particular scenario, though, did not have a methodology for estimating the VMT associated with unoccupied robo-taxis (also called zero-occupant vehicles [ZOVs]) that could replace on-demand or fixed transit. It is apparent that vehicle ownership—and overall vehicle availability— needs to be considered paramount when looking at the effects of wide-scale deployment of AV/CVs.

ANALYSIS OF THE MODEL RESULTS

The first three scenarios specifically targeted potential capacity improvements once fully automated driving was widely deployed. Capacity enhancements tested included an additional freeway lane to simulate the presumption that lane widths would narrow and the need for two emergency shoulders would be retired and replaced with one. Researchers made another capacity enhancement to simulate a slight-to-modest signalized intersection improvement that might occur through a presupposed technology or system arrival algorithm that improved flow. The last three scenarios utilized the cumulative enhanced network system improvements from the first three scenarios but proportionally moved transit trips to a mixture of shared and single-occupant rides, all single-occupant trips, or all shared rides.

Below are the results of the six scenarios by different performance metrics. Data are presented for vehicle miles of travel, speed and travel time changes, delay, impacts on average trip length (minutes and miles), and effects of mode reorientation on traffic. All of the metrics presented are for the AM period traffic assignment results since this was the period with the greatest levels of congestion among the four time periods.

Vehicle Miles of Travel

The 2040 base forecast application, without modifications, has 16,975,034 total VMT during the three-hour AM peak period. The results of all six scenarios show an increase in AM period travel, as defined by overall AM period system VMT. Table 11 shows the total change in VMT for each of the six scenarios as well as the results of the all-of-nothing application (no capacity constraint).

Table 11. Changes in Total AM Period VMT by Scenario.

VMT by Scenario	Scenarios							
	Base	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**AON**
	16,795,034	17,187,458	17,947,172	17,993,762	18,112,750	18,124,662	18,055,190	18,270,971

Figure 26 further illustrates the VMT results of each scenario as well as the percent of VMT change relative to the 2040 base application. The scenarios with the greatest change compared to the base 2040 forecast application are Scenarios 4 and 5, which used the Scenario 3 network but proportionally moved transit trips to the SOV or HOV trip tables. Although not explicitly stated, increasing the capability of freeways and expressways to handle additional traffic underlies the latent demand for these facilities and highlights the amount of diversion that typically occurs under typical congested conditions. This idea was repudiated when researchers compared the overall VMT results associated with the AON assignment relative to Scenarios 2 and 3, which are strictly network-based alternatives that emphasize capacity enhancements associated with AV/CV implementation. There is very little difference between these two scenarios in total period VMT when compared to the AON total results. AV/CV, therefore, could potentially minimize traffic diversion onto non-freeway links during peak-period traffic conditions.

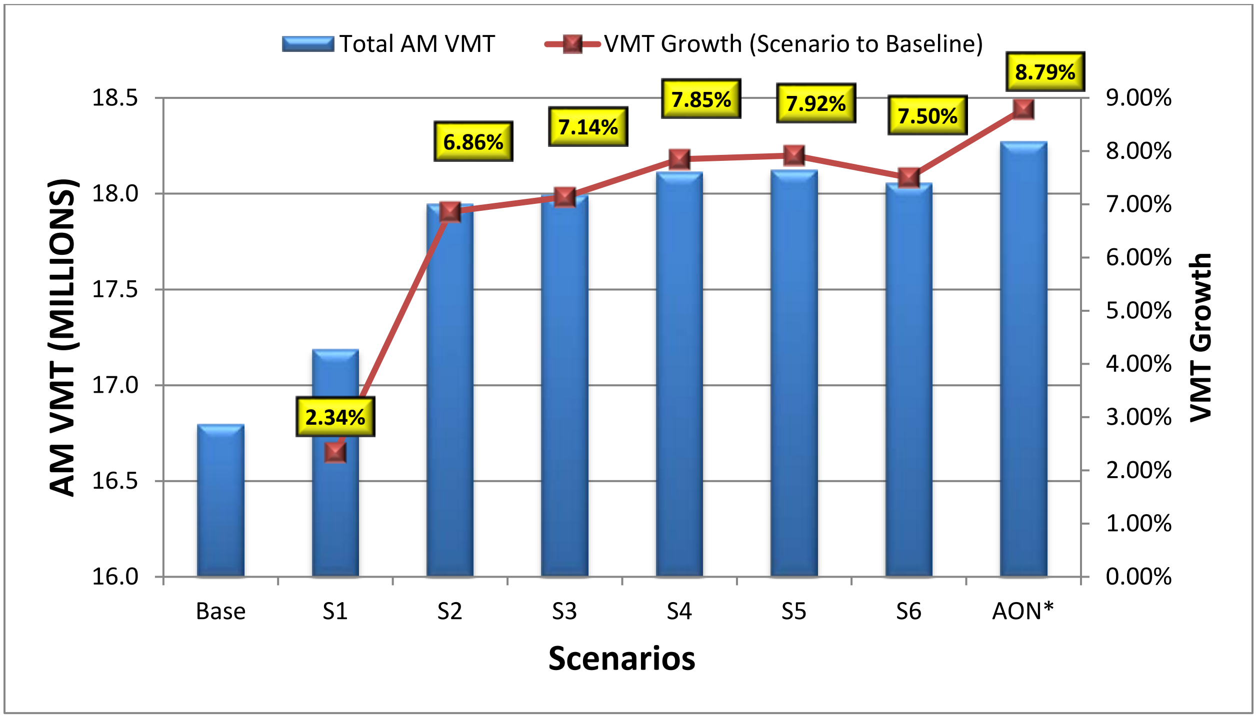


Figure 26. Changes in AM Period VMT.

Figure 27 shows the volume differences for the downtown portion of the Austin urbanized area expressed in bandwidths when the 2040 MTP or base AM period condition is compared to the Scenario 3 results. The bandwidths simply reflect the volume differences between the two assignment results. The links that are colored red are links that experience a decline in AM period traffic once the scenario edits are performed. The links that are colored green convey links that show an increase in overall traffic when compared to the 2040 base scenario. In this case, the edits are strictly network capacity edits. Nearly 1.2 million total vehicle miles of travel are added to the region’s overall travel in Scenario 3. As evident in the figure, much of this traffic reorients to the higher functional classifications (i.e., interstate system, U.S. highways) in the system, and the arterial and collector street systems generally experience declines in AM period traffic.

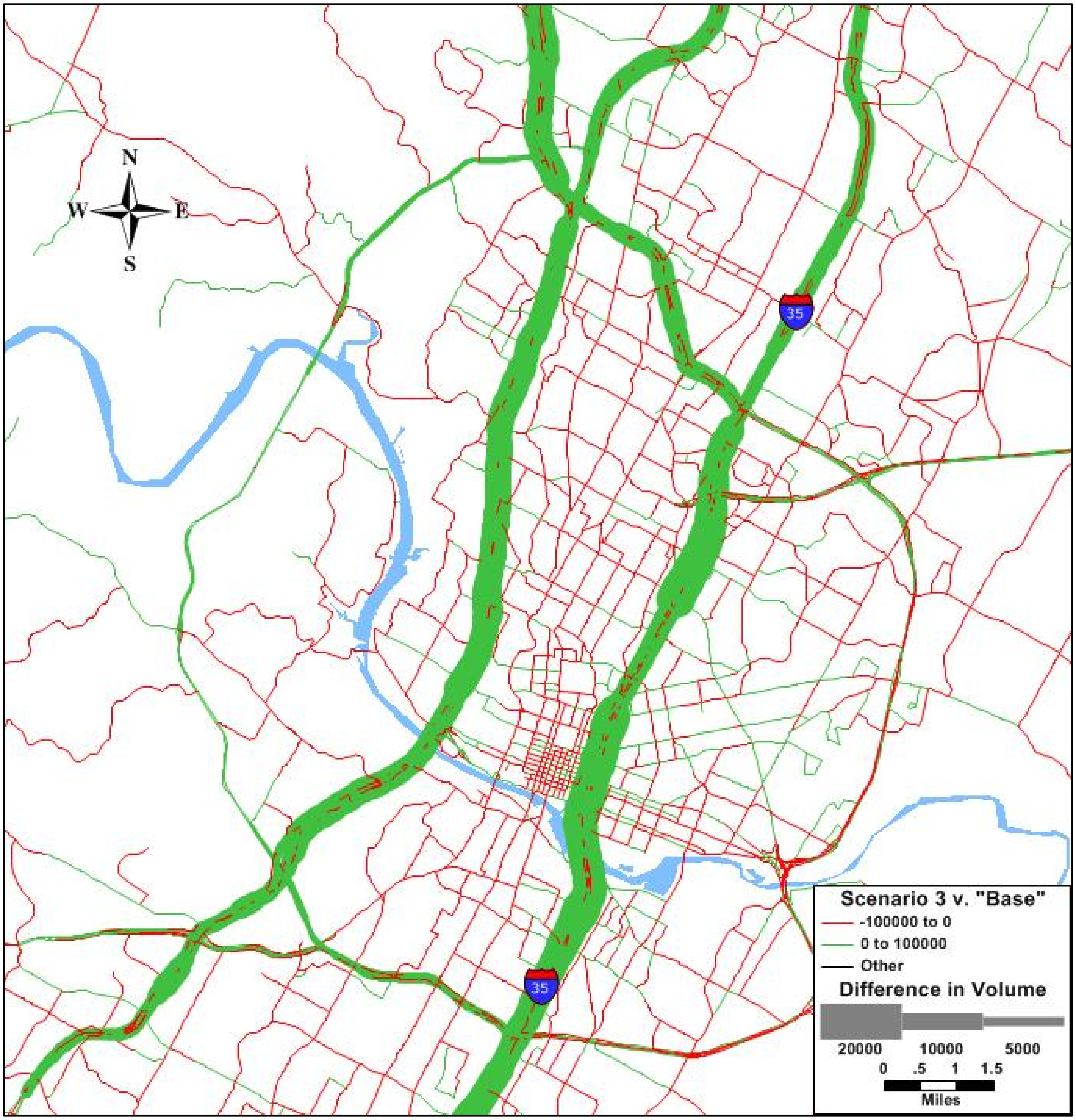


Figure 27. Volume Differences between 2040 MTP Base and AV/CV Scenario 3.

VMT and Congestion Levels

The amount of VMT occurring in different assigned volume-to-capacity (V/C) ratios provides a picture of the type of traffic that might be encountered by a typical driver during the highest hour of the three-hour AM period in 2040. As such, researchers analyzed four different V/C ratios:

- Less than 0.85 percent (low congestion).
- 0.85 percent to 1.00 percent (approaching link-level capacity).

- 1.00 percent to 1.15 percent (exceeding link-level capacity).
- Greater than 1.15 percent (high congestion).

Traffic diversion due to congestion typically occurs at around 85 percent of the available capacity during the capacity restraint assignment technique. Demand models—unlike operational models, which are capacity constrained (i.e., there is a physical limitation to amount of traffic allowed on a link)—will permit traffic to exceed the available capacity. Thus, travel models express corridor and system demand relative to the available capacity. Individual links will therefore be allowed to exceed the 100 percent capacity threshold.

It is interesting to examine the results of the six scenarios relative to both the base application and the AON application. Nearly 75 percent of the total VMT occurring in the morning period is traveling in what could be defined as relatively uncongested conditions in the base condition. This means, however, that 4.2 million VMT is experiencing roadway travel that is near or above the available period capacity of the link (i.e., greater than 85 percent volume-to-capacity ratio). Conversely, the amount of traffic that experiences a similar condition is reduced to approximately 1.2 million VMT in Scenario 3. Figure 28 illustrates the VMT by each of the four V/C ratios as well as the amount of traffic occurring below 85 percent of the available capacity. As the networks are improved, the amount of uncongested travel during the AM period is increased. Scenario 3 represents the apex of the improvements, while the remaining three scenarios represent only a small decline in uncongested travel after transit trips are reoriented to vehicle trips of different mixes. The all-or-nothing application shows a more even distribution of travel, but the percent of uncongested travel statistic is rather meaningless in the context of this assignment technique.

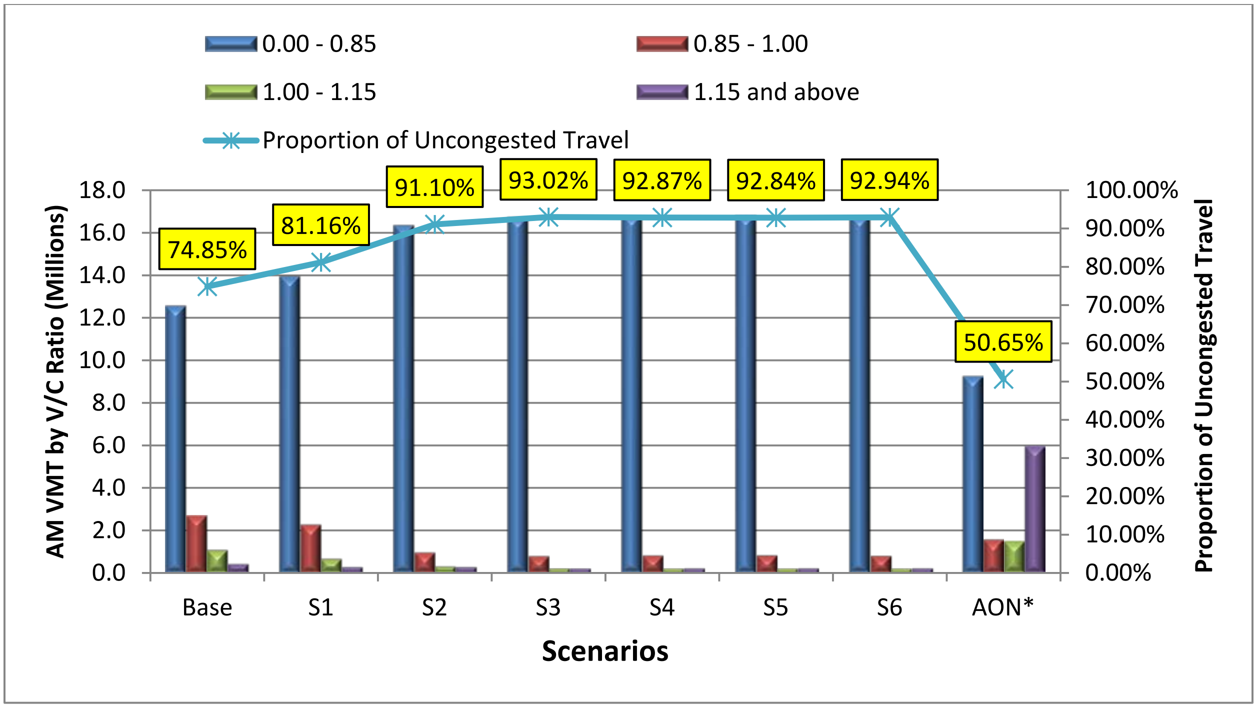


Figure 28. AM Period VMT by V/C Ratios.

Conversely, Figure 29 shows the amount of VMT that is occurring above the 85 percent threshold. In Scenario 3, a little less than 7 percent of the total VMT is occurring in the three most congested categories. Improving arterial flow between Scenarios 2 and 3 equates to a nearly 2 percent decrease in congested travel despite an overall increase in VMT.

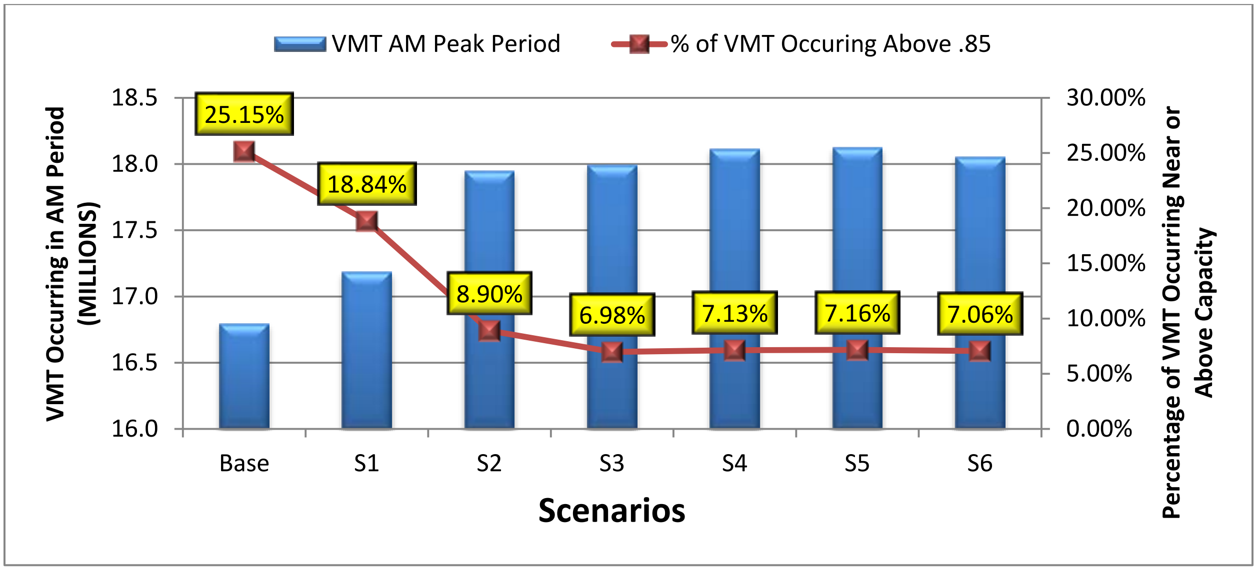


Figure 29. Percentage of VMT Near or Above Available Period Capacity.

Figure 30 graphically illustrates the level and type of AM period traffic congestion that will be occurring around the downtown portion of the Austin metropolitan area using the results from the 2040 base forecast application. Similar to today's congestion levels, the downtown area of Austin will experience significant link- and system-level congestion (considerably worse, however). The amount of traffic on individual links is expressed as bands in the figure. A smaller bandwidth has lower traffic volumes than a link with a wider band. The color theme depicts the V/C ratio of the period traffic.

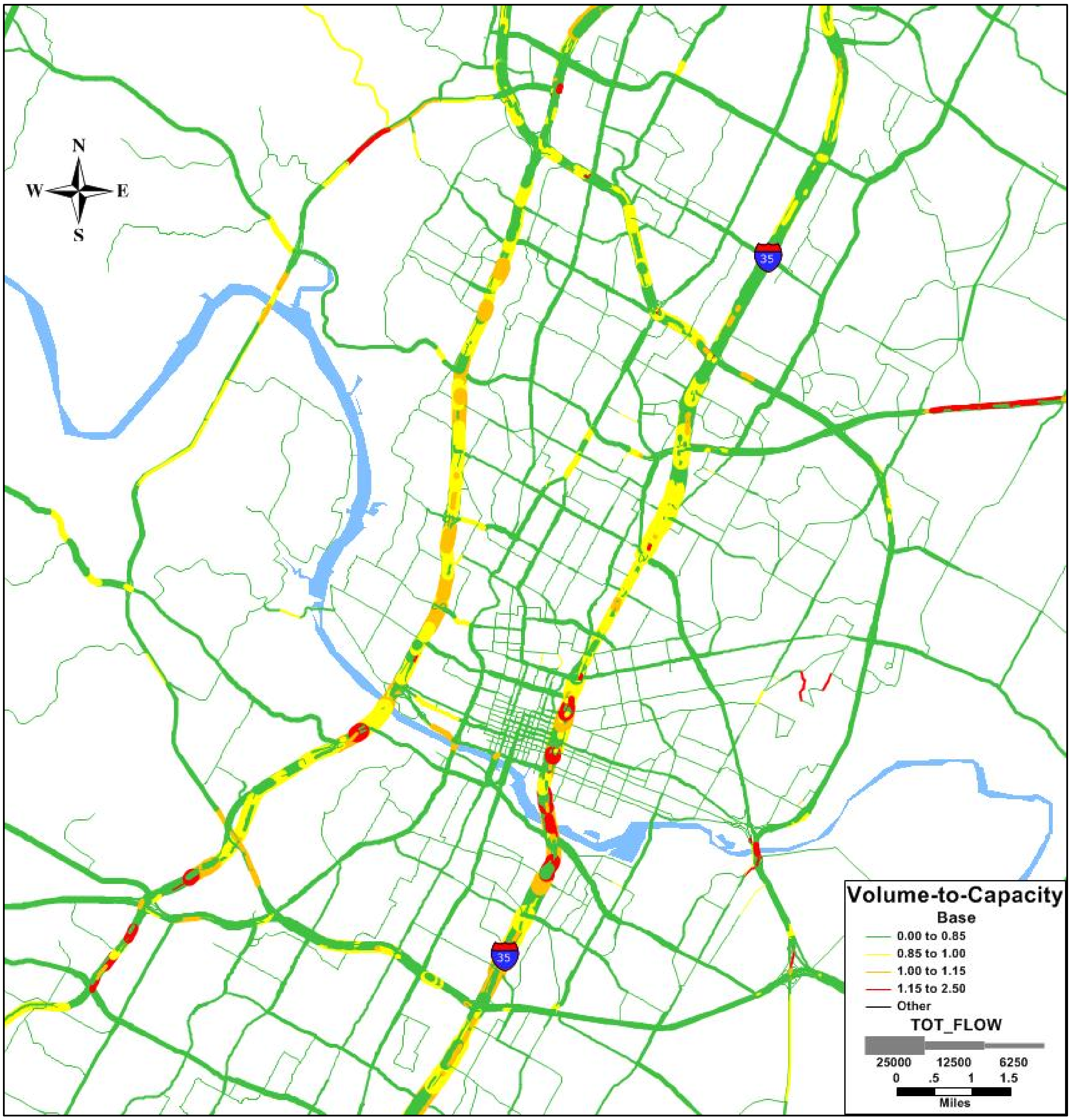


Figure 30. 2040 Base Scenario V/C Ratio Map.

Figure 31 visualizes the potential change that could occur when converting the one emergency lane to a thru lane, increasing the assumed per-lane capacity of all facilities that are expressways and above, and enhancing the total throughput of signalized intersections (10 percent capacity increase). This represents the cumulative network changes associated with the Scenario 3 alternative. The link volumes do change slightly, but the amount of congestion, as defined by V/C ratio, changes quite a bit in this alternative.

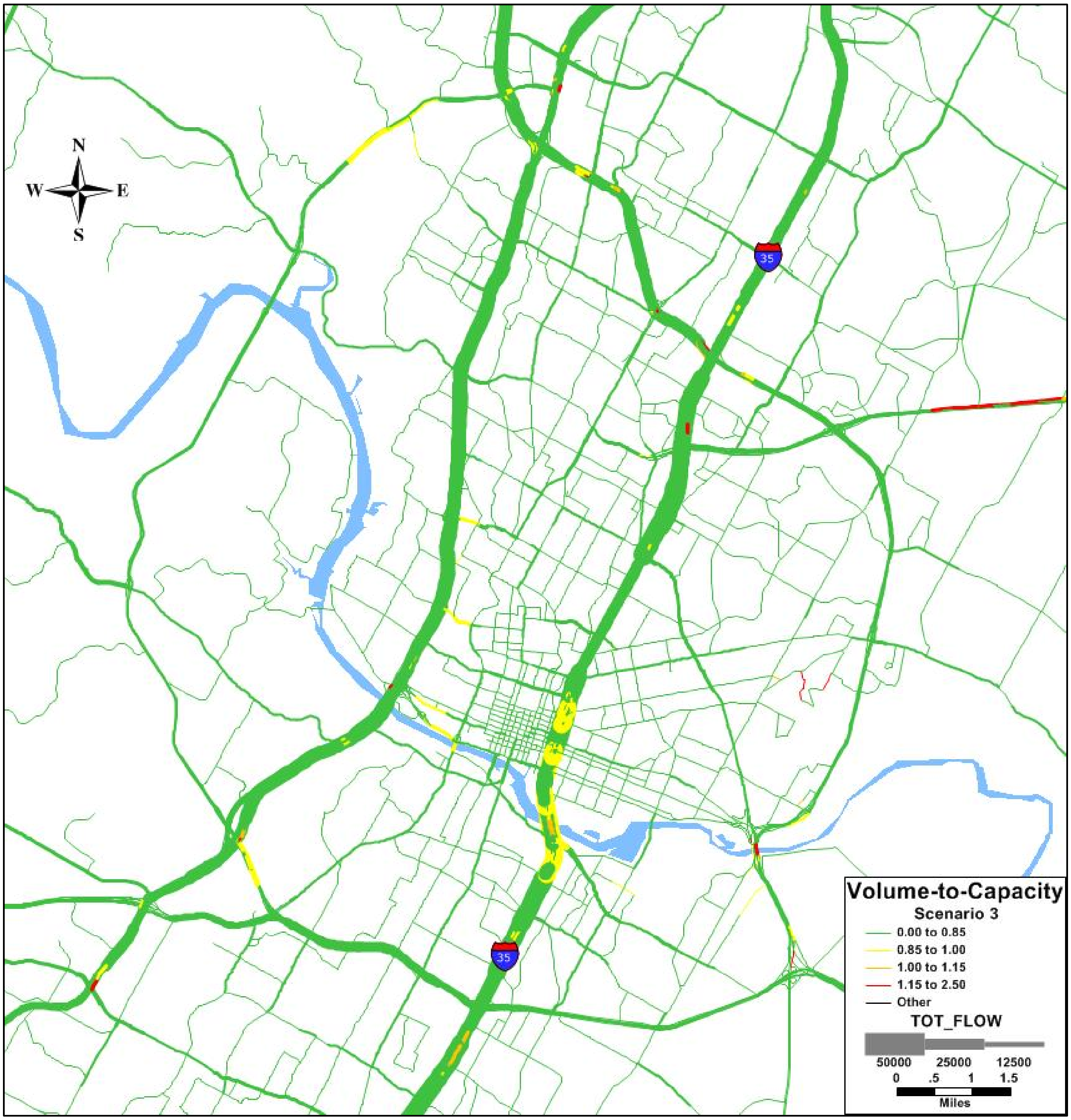


Figure 31. Scenario 3 V/C Ratio Results.

Changes in Speeds

The research team conducted a further examination of the VMT relative to resulting speed changes. As Figure 32 shows, as capacity enhancements are achieved in a fully autonomous system, the speeds generally encountered throughout the system increase. This in turn decreases travel times. The speeds were calculated using the resulting assigned speeds from the traffic assignment models. Figure 32 illustrates the change in VMT that occurs in 14 speed bins as a result of implementing the six scenarios compared to the 2040 base application. The speed bins are consistent with the categories used in previous air quality modeling (i.e., MOBILE6). Figure 32 shows only the comparative results of the six scenarios to the base condition. Although not directly presented in Figure 32, a significant proportion of the VMT in the base forecast application occurs in the mid- to lower-level speed ranges, while a smaller amount of traffic occurs in the higher speed ranges (i.e., above 42.5 mph). Conversely, Scenarios 2 through 6 show significant improvements in system speeds. Much more of the traffic is traveling at higher rates of speed.

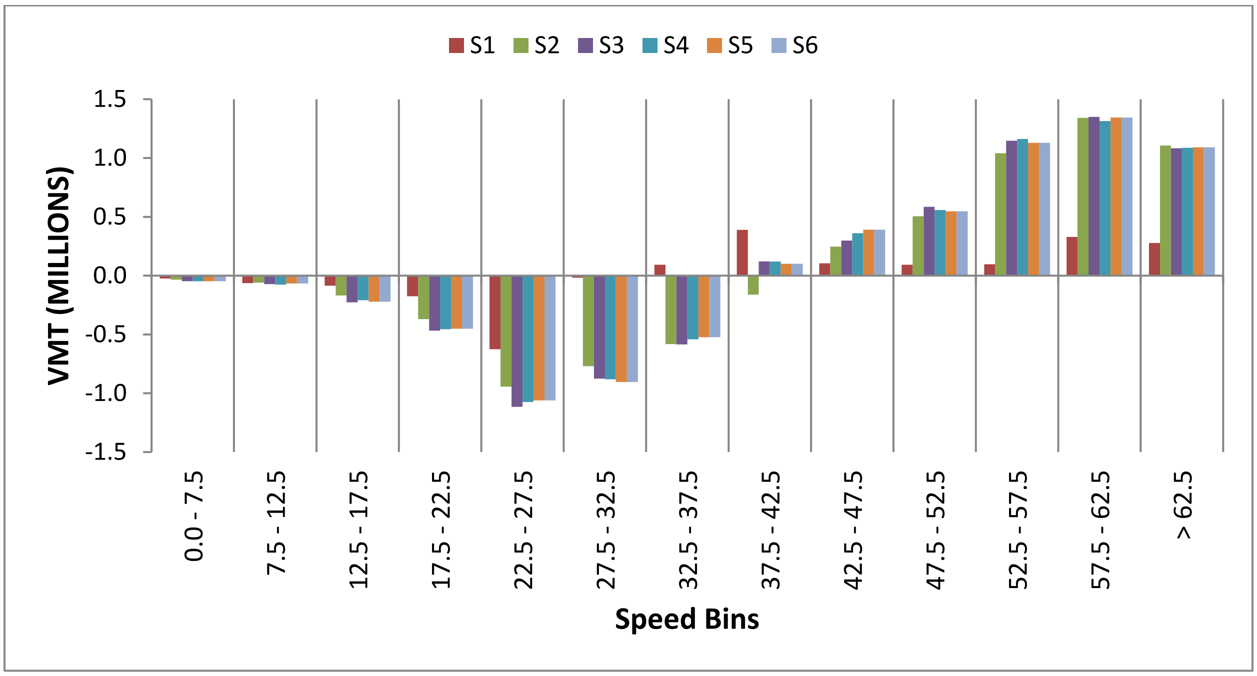


Figure 32. Total AM Period VMT Occurring by Speed.

Rather than continuing with the 14 air quality speed bins, researchers further reduced the categories from 14 to four to better illustrate the distributional changes that occur when alternative measures are implemented in each of the scenarios. The six scenarios are plotted against the base scenario in nearly 20 mph categories in Figure 33. The spike in the second speed category (22.5 mph to 42.5 mph) is replaced with a more even distribution of traffic for Scenarios 2 through 6.

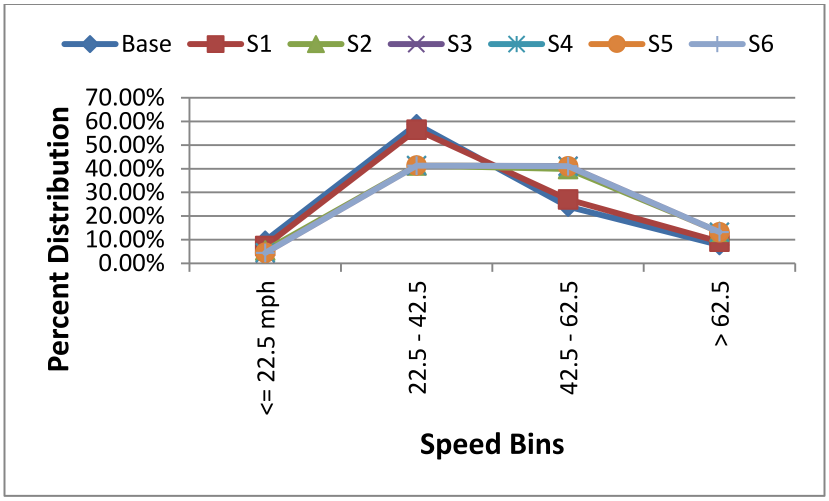


Figure 33. Distribution of VMT by Four Speed Categories.

The change in VMT that occurs within the four collapsed speed bins also communicates the degree of change that occurs once strategies are implemented. In Figure 34, the percent change of VMT by speed class relative to the base condition is plotted for each of the six scenarios. Proportionally distributing existing transit trips to SOV and/or HOV vehicle trips has very little influence on the resulting network speeds.

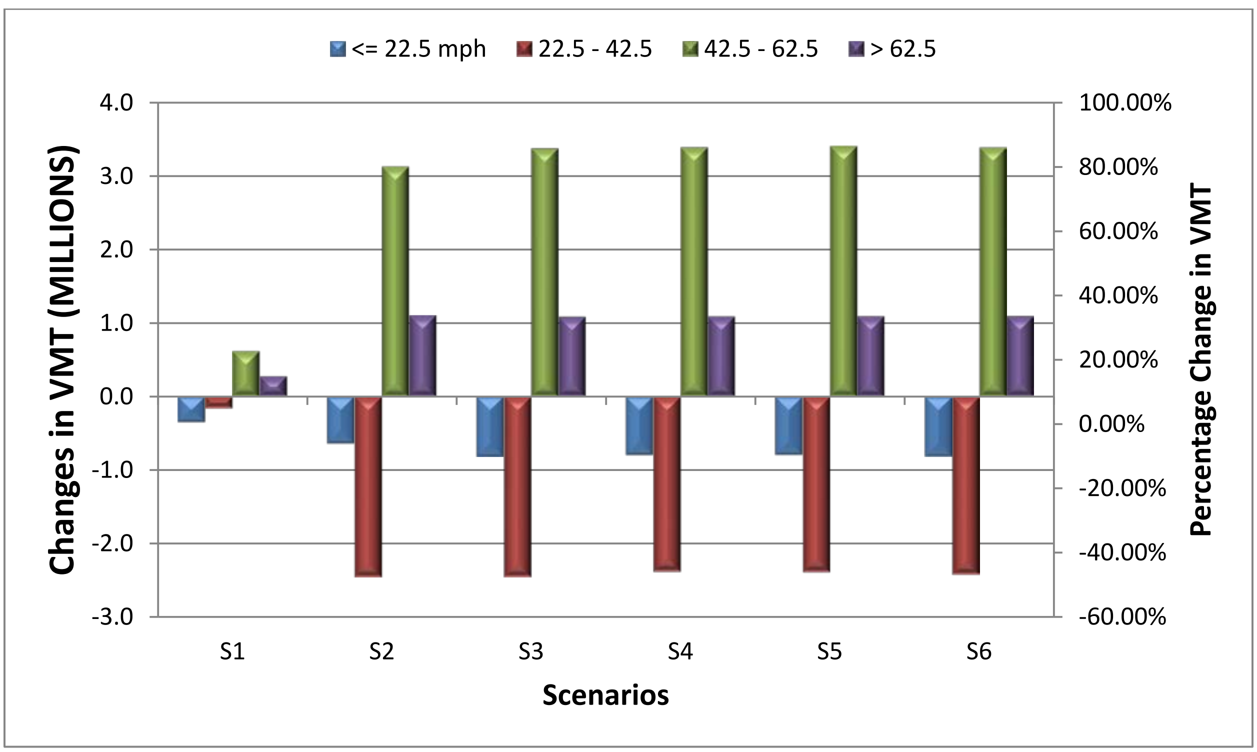


Figure 34. AM Period VMT Changes by Four Speed Bins.

Using isochronal travel time bands of 10-minute increments, the resulting congested travel time can be plotted relative to a common location in the Austin-area network geography. In this instance, the intersection of Congress Avenue and Riverside Drive is selected as the origin point of travel for the isochronal maps. Incidentally, this is the TxDOT-TPP Division Headquarters. Figure 35 illustrates the congested AM period travel time from this location to all other locations using the CAMPO 2040 base scenario.

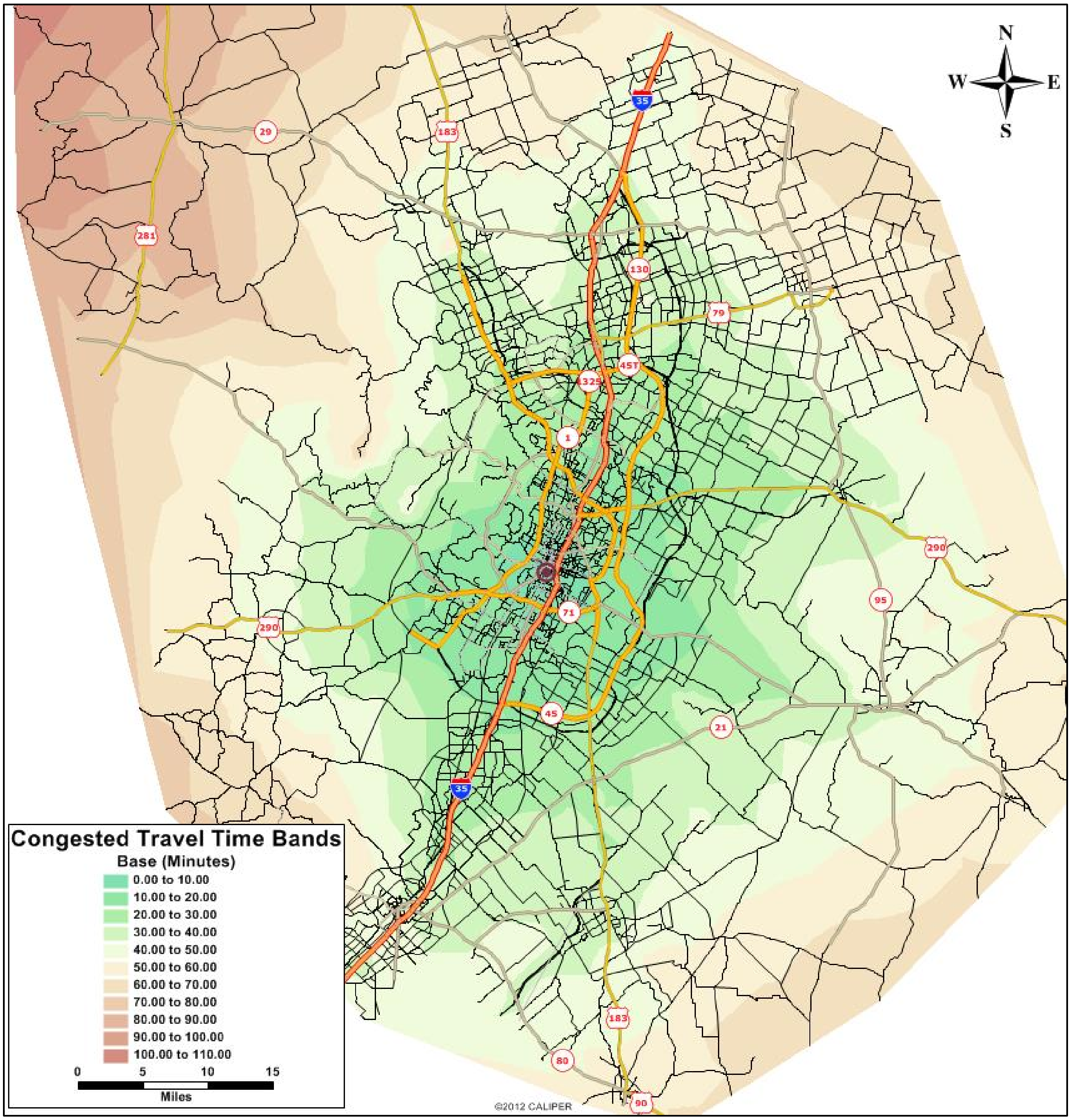


Figure 35. Base 2040 Network Travel Times from Downtown Austin (TxDOT-TPP).

Figure 36 illustrates the congested AM period travel time from this same location but uses the cumulative network improvements that resulted from the implementation of Scenario 3 characteristics. System travel times reflect less congestion in Scenario 3 versus the current long-range MTP scenario.

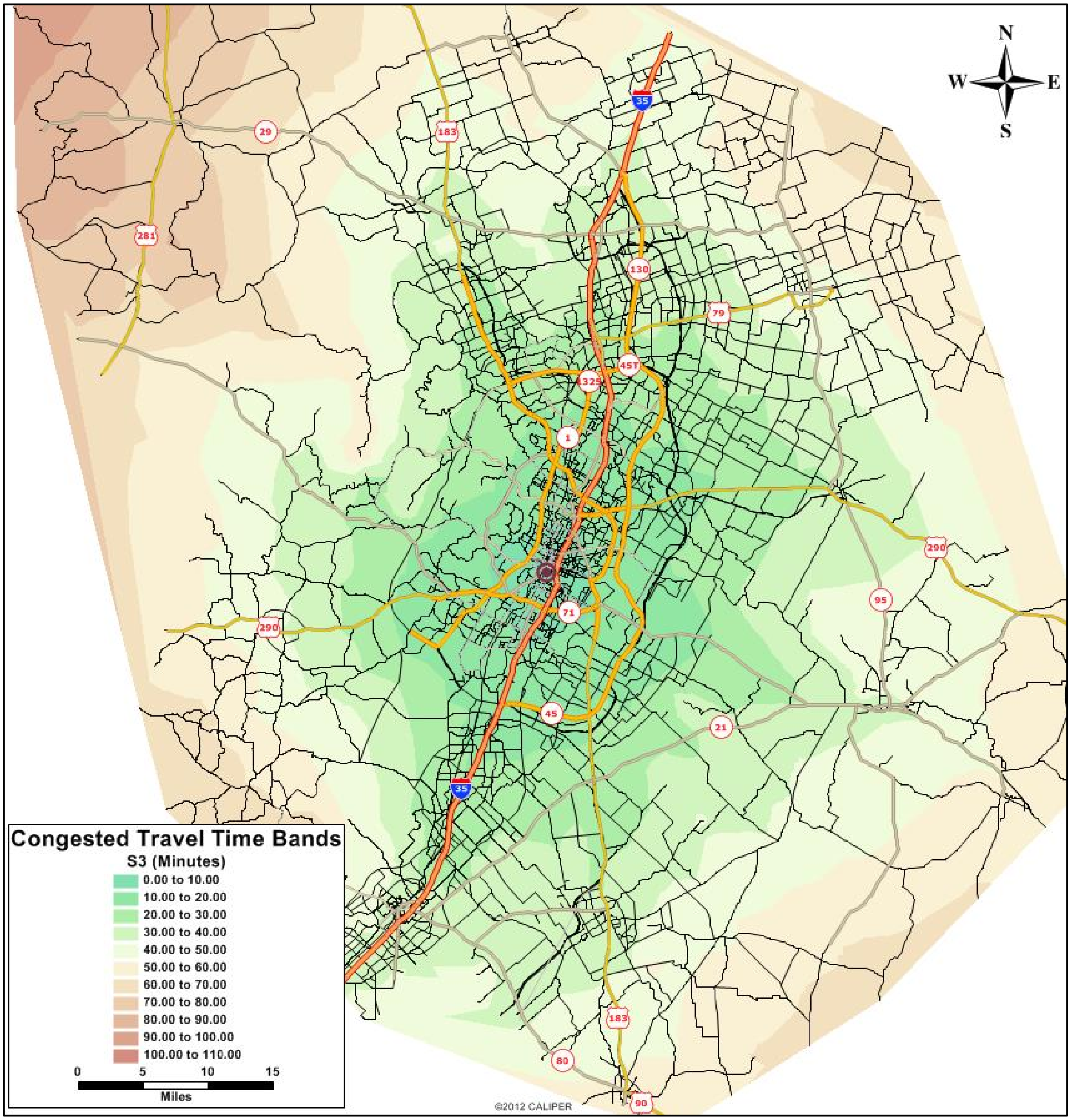


Figure 36. 2040 Scenario 3 Network Travel Times from Downtown Austin (TxDOT-TPP).

Ratio of Congested Time to Free-Flow Time

With the isochronal images, it is sometimes difficult to portray the benefits or drawbacks when comparing one alternative to another without adjusting the amount of bands as well as the gap within each band. The congested travel time is derived from the resulting traffic assignment speeds. The CAMPO travel demand model uses an iterative feedback loop that resolves the speeds/travel times between the trip distribution, mode choice, and traffic assignment steps. The travel time used to seed the initial trip distribution application is free-flow travel time conditions. For this study, the ratio of the congested AM period travel time to the free-flow AM period travel time was derived and the percentage change of each ratio was compared to the base 2040 condition. The results are presented in Figure 37. Scenario 1 (converting an emergency lane to a thru lane) shows a nearly 6 percent reduction in congested travel relative to free-flow conditions. The remaining capacity improvement alternatives (Scenarios 2 and 3) also show significant reductions in the travel time ratio when compared to the base-year condition. In this instance, the results of the all-or-nothing assignment are also presented in the figure to demonstrate that with all of the system-level performance improvements encountered by the six scenarios, the results still cannot match the overall conditions that can be achieved without capacity restraint. Thus, technology appears to potentially offer tremendous congestion and travel time improvements, but given the level of demand growth in the Austin region, the technology of self-driving cars cannot satisfy all of the expected demand. This is a potentially significant finding.

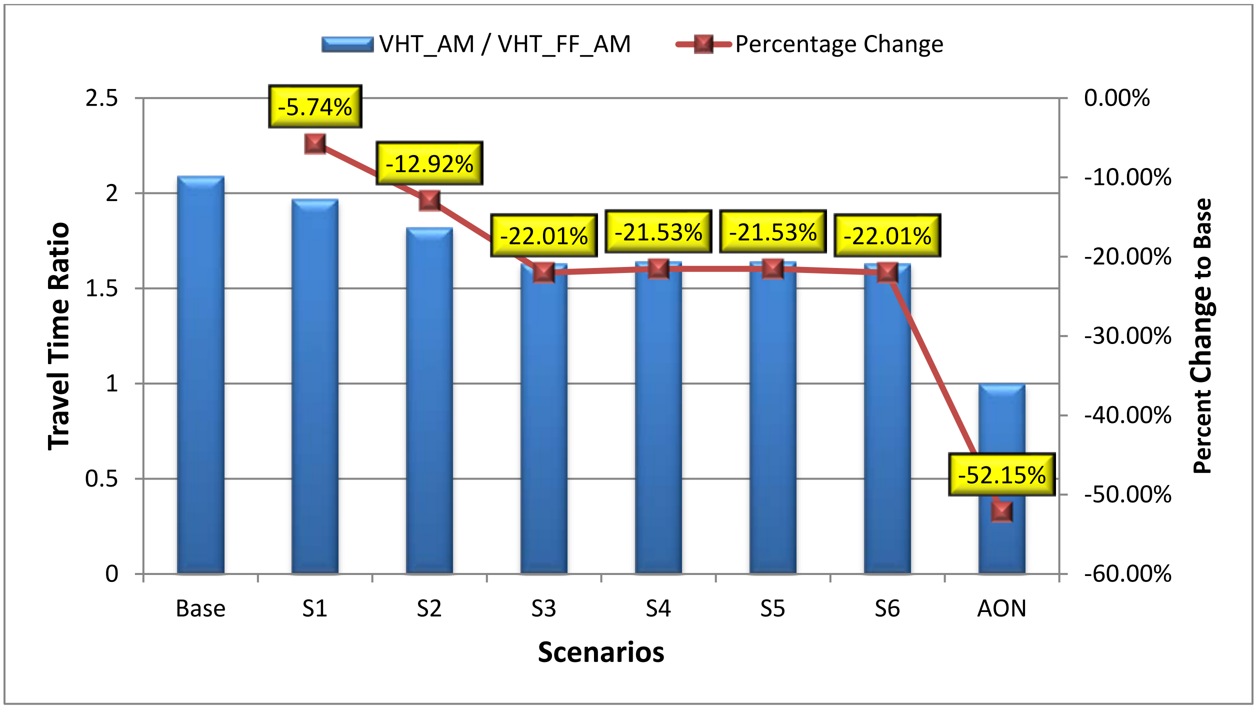


Figure 37. Ratio of Congested Travel Time to Free-Flow Travel Time (AM Period).

Changes in Delay and Vehicle Hours of Travel

The total amount of VMT increases with each scenario studied. The capacity improvements on expressways and freeways make these facilities more attractive. The posted speeds are much higher than the collector and arterial street system because of the associated access control. Additionally, when transit riders are proportionally moved to SOV and HOV trips in the trip tables, these additional vehicle trips increase the vehicle demand on the system. Because of these factors, the VMT increases with each AV/CV scenario in comparison to the 2040 base scenario.

Figure 38 illustrates the relationship between increasing VMT and declining delay per person. On the surface, this finding appears counterintuitive. The 2040 input demographics forecast 4,078,714 people for the six-county Austin model area boundary (MAB). The total 2040 population is an increase of 137.54 percent to the 2010 six-county population control total. Approximately 2.3 million people are expected to be added to the region during the 30-year period. There are 1,717,092 people in the 2010 base-year model.

Since more trips are being loaded to higher-class facilities, these tend to be longer trips but at higher speeds. Thus, the VHT declines for all six AV/CV scenarios relative to the base 2040 application but with corresponding increases in period system VMT.

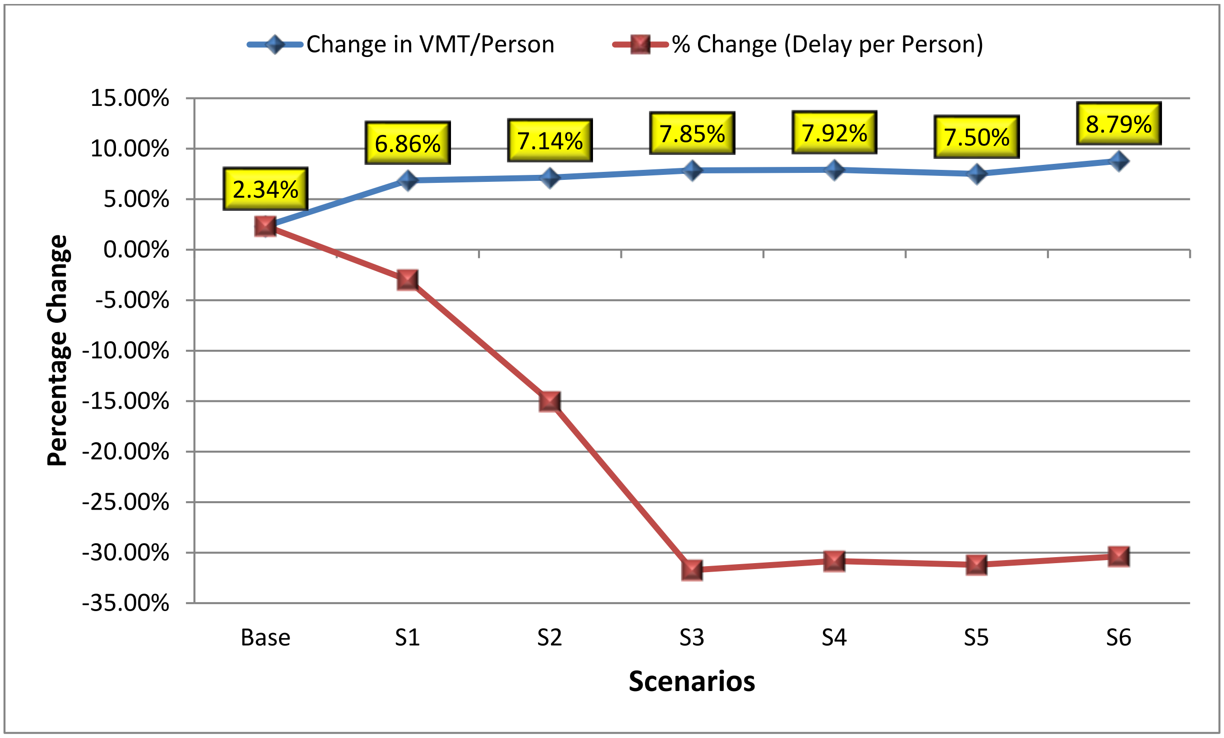


Figure 38. Changes in Person-Level VMT and VHT (AM Period).

Figure 39 shows the total vehicle hours of delay for each AV/CV scenario and the base 2040 forecast application. Along with the presentation of total delay, the figure also shows the average per-person delay (expressed in minutes) during the AM period. The first three AV/CV scenarios, which can each be considered capacity enhancement scenarios, show both total and per-person delay declines. The greatest total decline is between the 2040 forecast and the cumulative network changes implemented in Scenario 3. A full two minutes and nine seconds of delay is removed on average for each traveler during this period. This represents a total AM period delay reduction of 146,634 person-hours when compared to the 2040 MTP forecast.

Travel represents all travel and not just travel generated by households in the region. The VMT also includes traffic that results from external traffic to the region. The redistribution of transit trips to auto trips results in only minor uptick in total and per-person delay.

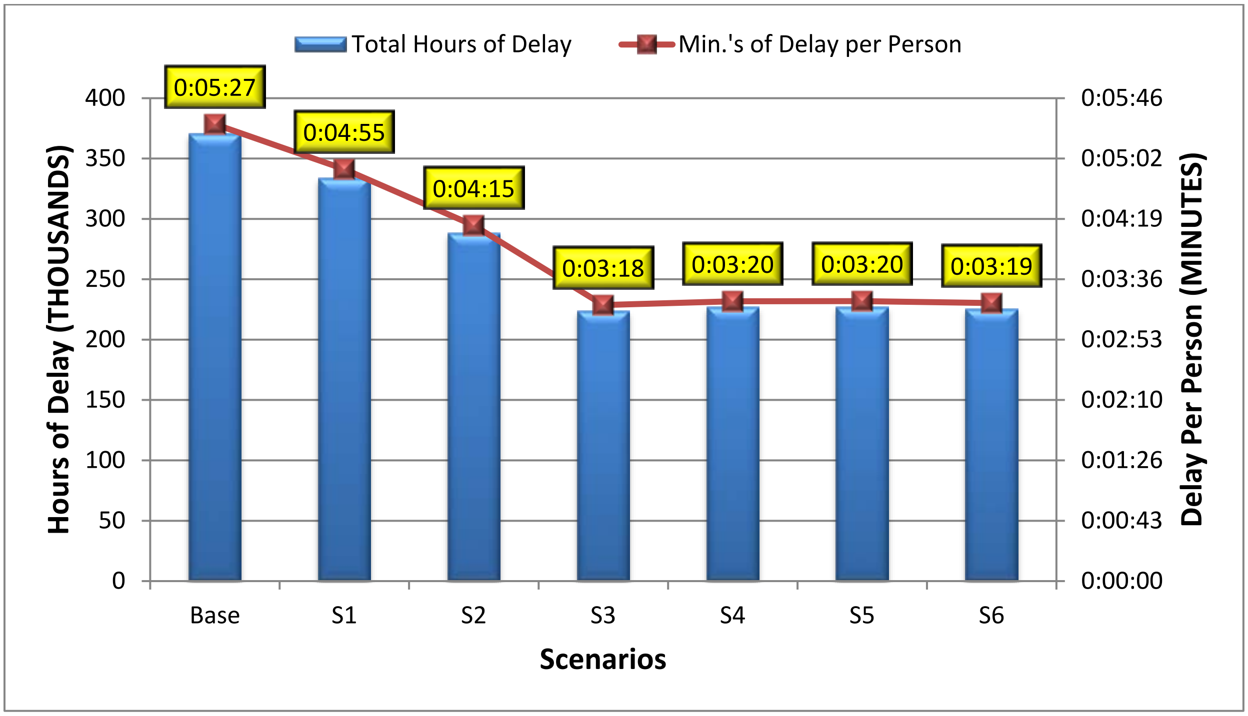


Figure 39. Total Delay and Per-Person Delay.

Changes in Average Trip Length in Minutes and Miles

To further emphasize the change in trip orientation to longer but quicker routes (travel time), researchers analyzed the resulting average trip length in minutes and miles for each of the six AV/CV scenarios. Two figures were created using output data from the assignment models. The first figure, Figure 40, shows the average trip length (ATL) of all AM period trips as well as the percent decline in ATL relative to the original 2040 base scenario. The most significant decline is evident in Scenario 3, which combines capacity enhancements for freeway and non-freeway facilities.

For non-freeway facilities, the capacity throughput of signalized roadways was improved by 10 percent. The capacity improvement for these facilities is not nearly as great as it was for expressways and freeways studied. This finding is largely due to the fact that given saturation demand conditions at signalized intersections, there can only be limited improvement achieved. If vehicles arrive at an intersection randomly, then as volume increases from all approaches to the intersection, it is very probable that many vehicles will be delayed during the red phase of the signal cycle. Without coordinated arrivals, little can improve signalized intersection capacity.

What this analysis does not take into account is the very real possibility of robo-taxis being present in the system, which is briefly discussed later in the chapter.

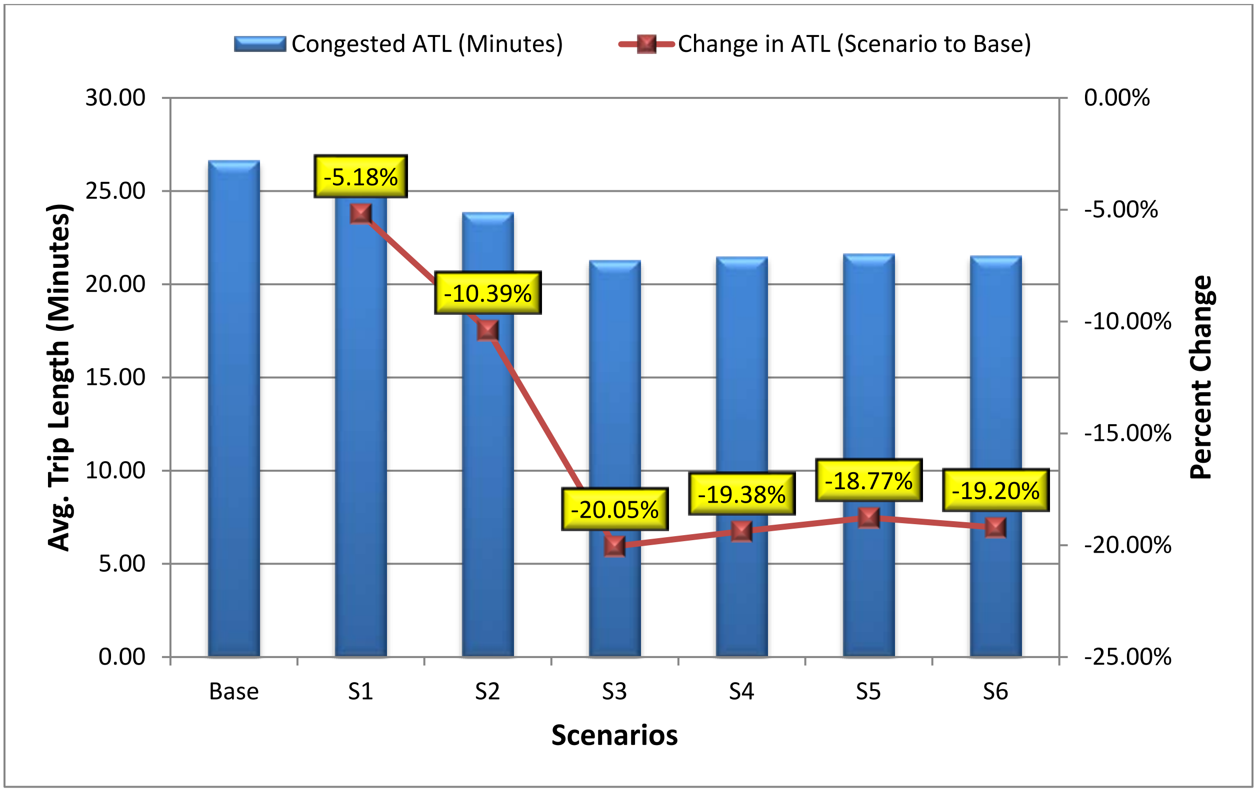


Figure 40. Changes in Congested Average Trip Length (Minutes).

The second figure created was Figure 41, which shows the total number of trips for each scenario. The base 2040 condition has 1,599,279 trips during the three-hour AM period. As capacity improvements are made to the remaining scenario networks, these total trips increase slightly. The average trip length in miles, unlike minutes, increases for all conditions when compared to the base. The largest increase in ATL (expressed in miles) is for Scenario 5, which uses the modified network from Scenario 3 and moves all transit trips that are output from the mode choice model to the SOV trip tables. Therefore, completely replacing fixed transit with all single-occupant autos would contribute to greater traffic. Regionally, the increased traffic might not be considered appreciable, but on a corridor or sub-area of the study, it might be quite evident.

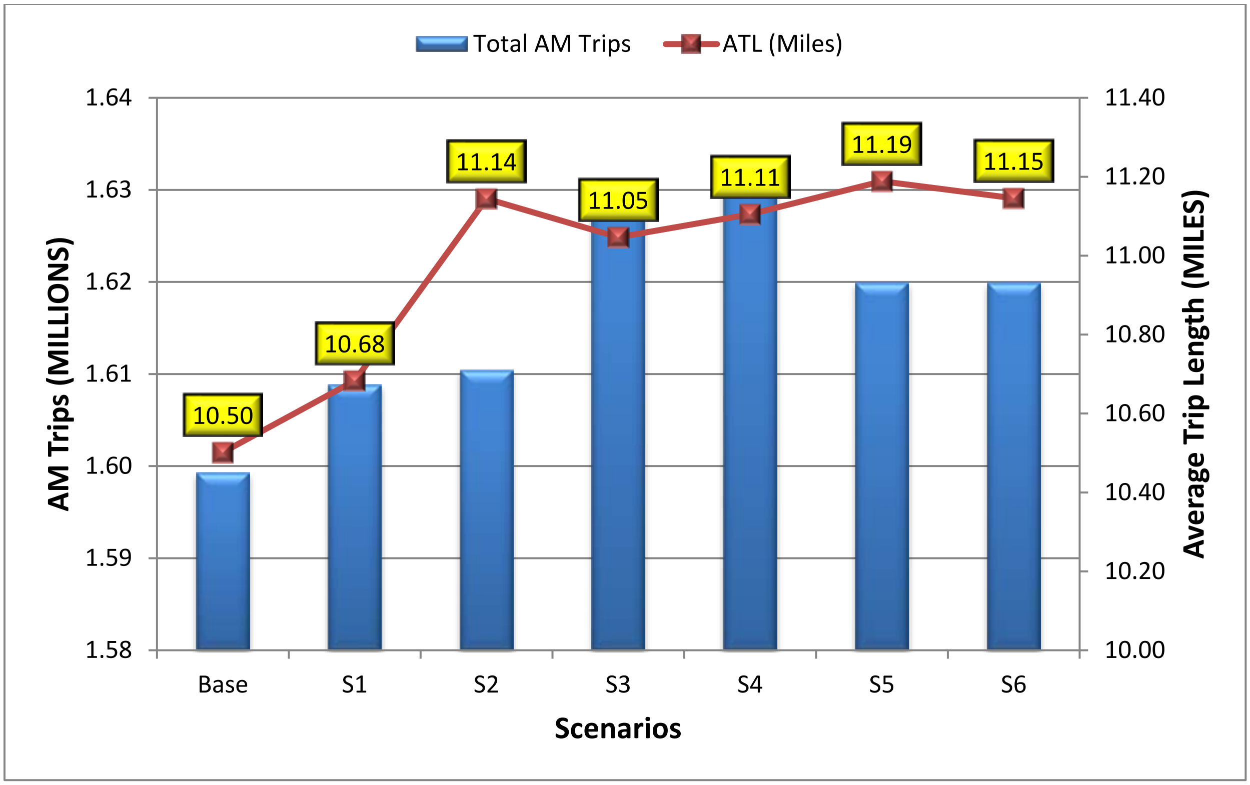


Figure 41. Total AM Period Trips and Changes in Average Trip Length in Miles.

Changes in Mode (Transit)

The last three scenarios, 4 through 6, involve some level of proportional distribution of person transit trips to vehicle trips. This work was manually accomplished after the mode choice models were applied. Each of these scenarios uses the edited network geography from Scenario 3.

The research team applied the scenarios to determine the level of impact that would occur if fixed-transit service were no longer necessary because of the increased automated auto availability and affordability. The transit trips would be replaced with either SOV trips or a combination of HOV and SOV trips. The three scenarios are:

- Scenario 4—Utilize the Scenario 3 network geography and proportionally move the transit trips to SOV and HOV (2 and 3+).
- Scenario 5—Utilize the Scenario 3 network geography and proportionally move the transit trips to SOV only (no HOV).
- Scenario 6—Utilize the Scenario 3 network geography and proportionally move all of the trips to HOV 2 or HOV 3+ trip tables.

Figure 42 shows the total number of transit trips by scenario. There are imperceptibly small differences for the first three scenarios, but as noted in the bullets above, there are no transit trips for the last three remaining scenarios (Scenarios 4 through 6). The decline in total transit trips between the base application and the first AV/CV scenario application has to do with increased expressway/freeway capacity enhancements and corresponding increases in network congested speeds and declines in overall network delay. Figure 42 also shows the decline in passenger miles traveled for each scenario.

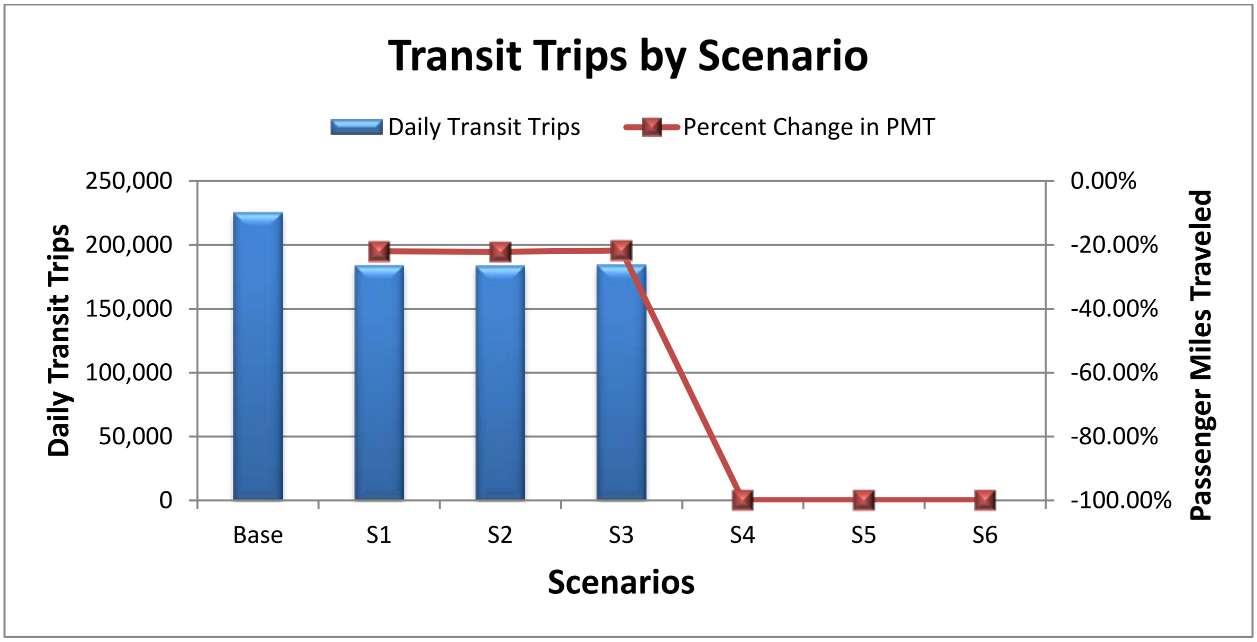


Figure 42. Transit Trips by Scenario.

SUMMARY OF FINDINGS

As evident from the six AV/CV applications, reactions and corresponding metrics that result from these tests show fairly significant changes in AM period travel using the 2040 Austin (CAMPO) travel demand model. In general, overall system travel increases, while average travel times decline. The travel increases are presumably associated with improved traffic flows that were achieved by altering the underlying capacity assumptions for freeway and arterial facilities. It is not clear whether the magnitude of the changes studied will ultimately be achieved once the driving fleet is fully autonomous and connected. Presumably, a completely integrated AV/CV fleet of vehicles could alter saturation flow rates through any number of changes. These changes could include:

- Controlled vehicle gap distances.
- Narrower lanes.
- Smaller vehicles.
- Fewer incidents.
- Coordinated intersection controls.
- Coordinated arrival systems and speed harmonization.
- Departure/arrival coordination.
- Truck fleet mix.

- Percent of peak-hour traffic.
- Shared rides.

Table 12 shows the general trends associated with the six scenarios relative to the 2040 MTP traffic assignment results (base).

Table 12. General Travel Trends of AV/CV Scenarios Relative to Base Forecast.

Metric	Trend
AM Peak-Period VMT • Region • Per Person	↑
AM Peak-Period Travel Time • Travel in Uncongested Conditions • Travel in Congested Conditions	↑ ↓
AM Congested Weighted Speeds	↑
AM Travel Time Delay	↓
AM Average Trip Length • Minutes • Miles	↓ ↑
Mode Shares (Transit)	↓

ENUMERATING UNCERTAINTY IN TRAVEL DEMAND MODELS

A number of different avenues could have been pursued to analyze the potential impacts of a fully connected and autonomous transportation system. Potential outcomes could be studied individually or collectively, and more to the point, there could be any number of transformative events that could occur before the entire system is integrated (e.g., economy, energy). Arguments and counter-arguments can be made for a host of anticipated changes that may occur, all of which contribute to the uncertainty associated with studying the potential impacts on travel demand. In addition, there could be numerous unintended consequences associated with full rollout and adoption of the enabling technologies (e.g., disutility to travel deceases to an extent that further sprawling land use results).

Table 13 lists the major model components and inputs in the existing 2010–2040 CAMPO TDM. Potential sensitivities associated with various inputs toward AV/CV technology are briefly discussed.

Table 13. List of Trip-Based Inputs and Uncertainty.

Component	Input	Sensitivity	Further Comment
Socioeconomic Data			
	Number of households	Will there be overall regional growth sensitivity to economic conditions impacted by AV/CV?	
	Household income	Same as above.	
	Land use distribution	Will parking elimination due to AV/CV free up land for in-fill development? Or will sprawl ensue due to decreased disutility of travel time?	
	Employment	Will telecommuting and alternate workplace locations become the norm?	
	Basic	Will large distribution centers still be appropriate or more appropriate? Will the economy still move toward service-related jobs?	Not tested because of speculative nature of changing these inputs.
	Retail	Will big-box retailers even be appropriate? Could anticipate new order-delivery systems.	
	Service	Will service employment continue to increase?	
	Education	Will K-12 locations change because of increased accessibility?	
	Special generators	Will there be fundamental changes to trip attractions and productions from traditional special generators of traffic?	

Table 13. List of Trip-Based Inputs and Uncertainty (Continued).

Component	Input	Sensitivity	Further Comment
Highway Network			
	Lanes	Will two emergency lanes be necessary on future freeways? Can one emergency lane be retired? Can the width of lanes be narrowed due to greater vehicle safety control?	Retirement of one emergency lane tested.
Capacities	Freeways	Will saturation flow rates improve with greater control of individual vehicles?	Increased per-lane capacity for all freeway and expressway mainlanes.
	Signalized facilities	Will there be improved signalized intersection flow? Coordinated arrivals?	Tested 10% improvement in arterial-level capacities per lane.
	Time-of-day expansion factors	Will these no longer be necessary because of AV/CV impacts on capacity?	
	Area types	Will the influence of adjacent land use, signal spacing, and curb cut spacing be minimized?	Tested unified freeway level per-lane capacity for all area types.
Geographies			
	Model area boundaries	Could the need to expand MABs increase if external travel increases because of new household locational criteria?	
	Sectors	Could certain sectors or portions of the study area (e.g., CBDs) become robo-taxi only?	
	Traffic analysis zones		

Table 13. List of Trip-Based Inputs and Uncertainty (Continued).

Component	Input	Sensitivity	Further Comment
Trip Generation			
Household distributions	Household size	Might there be new measures of household wealth to reflect travel?	
	Household income		
	Workers per household		
	Vehicle availability (autos per household)	Will vehicle ownership rates change? Will overall auto availability change due to robo-taxis?	
Trip rates	Production	Travel cost—and value of time—could change due to AV/CV, which affects trip frequency.	More or less total travel?
	Attraction		More or less travel by trip purpose? Could be less travel for shopping, but more for recreation?
	Truck/freight	Will freight delivery/distribution fundamentally change?	
	External	Will external travel expand further because it will be easier to live farther out?	
Trip Distribution			
Time	Skims	Will networks speed up because of capacity changes?	
	Friction factors	Will disutility to travel based on spatial separation change?	
	Average travel times	Will these increase or decrease by trip purpose?	
	Bias factors		Not used in current CAMPO models.
	Composite	Will costs of travel or how travel cost is paid fundamentally change?	

Table 13. List of Trip-Based Inputs and Uncertainty (Continued).

Component	Input	Sensitivity	Further Comment
Mode Choice			
	Auto-occupancy factors	Will occupancy levels increase or decrease by trip purpose?	
	Transit networks	Will fixed transit (especially in major southwestern cities) be needed?	
	Accessibility	Will robo-taxis provide first-mile/last-mile access? Will cost of service be affordable?	
	Shares	Will non-auto shares increase or decrease?	
Time of Day			
	Time-of-day factors	Will peaks be minimized or spread out in the future?	
Traffic Assignment			
Vehicle miles of travel	Zero-occupant vehicles	Conceptually, vehicles could circulate throughout urban area for demand services.	How is this VMT accounted for?
Volume-delay functions (VDFs)	VDF	Will traffic diversion be controlled by some other means?	Perhaps by pre-planned, coordinated routing automation?
	Intersection delay	Will this be minimized?	
Specification?	Dynamic?		

Appendix F evaluates model components and potential AV/CV sensitivities relative to the H-GAC ABM. H-GAC is the only ABM model in the state. The adoption of the ABM model platform within the small- to medium-sized urban areas in the state is probably not eminent; nevertheless, it is worth noting how the ABM components can be altered to study AV/CV impacts (using the H-GAC ABM as an example).

LIMITATIONS OF CURRENT TRAVEL MODELS

Traditional three-step models are calibrated to base-year conditions, and the trip rates, friction factors, values of time, and costs are held constant for all forecast applications. The major components of change in a typical model forecasting application are demographics and networks. Trip rates and trip lengths are measured via the TxDOT travel survey program, and these values are not updated again until a new survey is collected and analyzed. This is worth noting since there is not any observed behavior that captures what might occur once the potentially transformative nature of AV/CV technology is fully or partially reflected in the fleet mix. Therefore, it is difficult to predict what effect these enabling technologies will have on travel-making characteristics, vehicle ownership, accessibility, and mode shares. Since the trip generation rates are aggregated to the household observation, future life-cycle characteristics of the household are not addressed in current trip generation models. It is not until individuals are simulated within the households that travel models react to these naturally occurring changes in the evolving nature of households.

It is also difficult to anticipate whether AV/CV technology will increase or decrease the independently mobile population once the driving task is removed. Conceptually, certain segments of the population may have greater access to independent mobility with the advent of AV/CVs. These are aging and impaired persons. Both cohorts are rarely adequately addressed in typical three- or four-step travel models. The research team performed a brief analysis to determine the potential outcomes that greater driver (or shared-ride) participation may contribute to a region's congestion levels.

Aging Drivers

In the state of Texas, teenagers can apply for a learner's permit at age 15 and obtain a provisional driver's license at age 16. A full driver's license is issued at age 18. Those under the age of 19 represent slightly less than 5 percent of the total licensed drivers in the state of Texas (*69*). On the other end of the spectrum, drivers that are 70 and older represent 8.83 percent of the total driving population using the latest figures from FHWA. Figure 43 illustrates the distribution of drivers in Texas by incremental age cohorts.

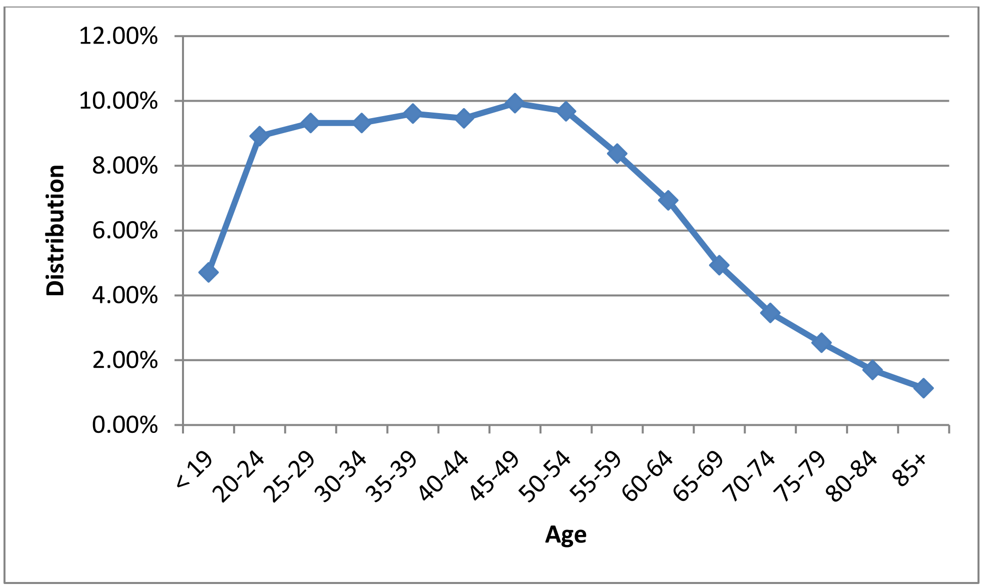


Figure 43. 2010 Age Distribution of Licensed Drivers in Texas (*69*).

In a fully autonomous and connected transportation system, might both cohorts (young drivers/pre-drivers and older drivers) see an increase in overall travel? Conceptually, this is possible. With respect to pre-drivers—those teens or children that are younger than age 15—a number of legal questions may arise that prevent higher participation, especially vehicle trips that lack adult supervision. For aging older drivers, access to mobility through either on-demand services or a self-driving car might encourage greater trip making. Consequently, fully autonomous vehicles, at least initially, may have a greater impact on the older population versus the pre-driving age population.

As noted earlier, the six-county Austin metropolitan area is expected to grow by more than 1.1 million people during the 30-year planning horizon between the 2010 base year and the 2040 forecast year application that is used to support the long-range MTP. The 2010 base-year population grows from 1.7 million people to nearly 2.9 million people by 2040, which represents a 64 percent increase in population growth. TSDC projects county population in one-year increments for different growth scenarios. Using the latest TSDC population projections for the six-county Austin region, the research team performed an analysis of the age-specific distributions within the forecast demographics.

The existing CAMPO model household production rates were then reevaluated using the new age and sex cohorts from the 2040 TSDC projections to estimate a potential impact on overall trip productions. In the state of Texas, production rates are weighted by age and sex cohorts, but once these rates are published, they are held constant for all forecast applications. Consequently, changes to these household life-cycle characteristics and subsequent effects on household travel characteristics are not truly captured in the current models. Other study areas in the state could conceivably perform a similar evaluation on the presumptive effects of aging and travel.

Aggregating the Austin-area one-year population projections into five-year cohorts, the percentage of people aged 70 and older grows from 5.41 percent of the population to more than 13 percent of the population in the year 2040. This finding is consistent with the general trends in the entire state, where 13.74 percent of the total population will exceed the age of 70 by 2040. Figure 44 illustrates cumulative five-year age distributions for the 2010 base year and the 2040 horizon year (*69*). The figure graphically depicts total aggregate changes within the five-year age categories.

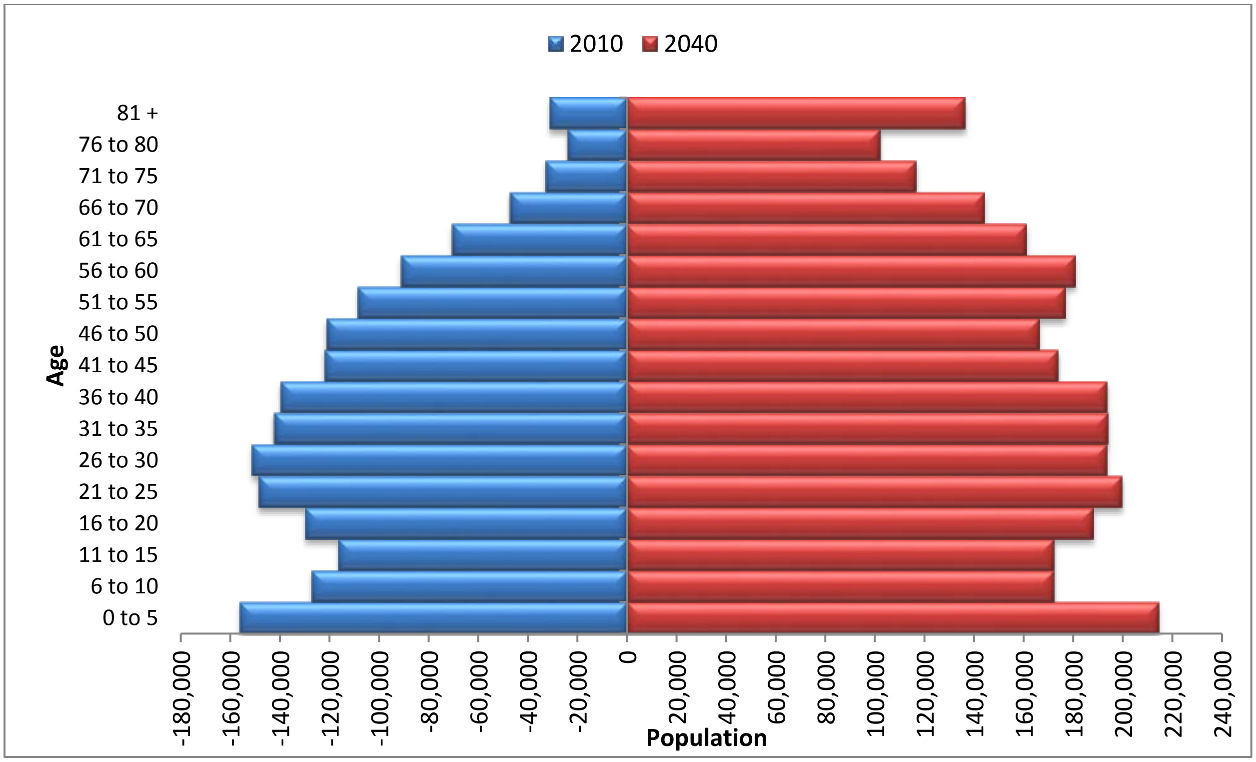


Figure 44. Austin-Area Population Pyramid by Age Cohorts.

Figure 45 uses the same data to illustrate the growth in population by five-year age increments relative to the total population growth. These data represent the six counties that are modeled by CAMPO. As evident in Figure 44, those people who will exceed 81 years of age will represent the largest proportion of overall and percentage growth in the Austin metropolitan area.

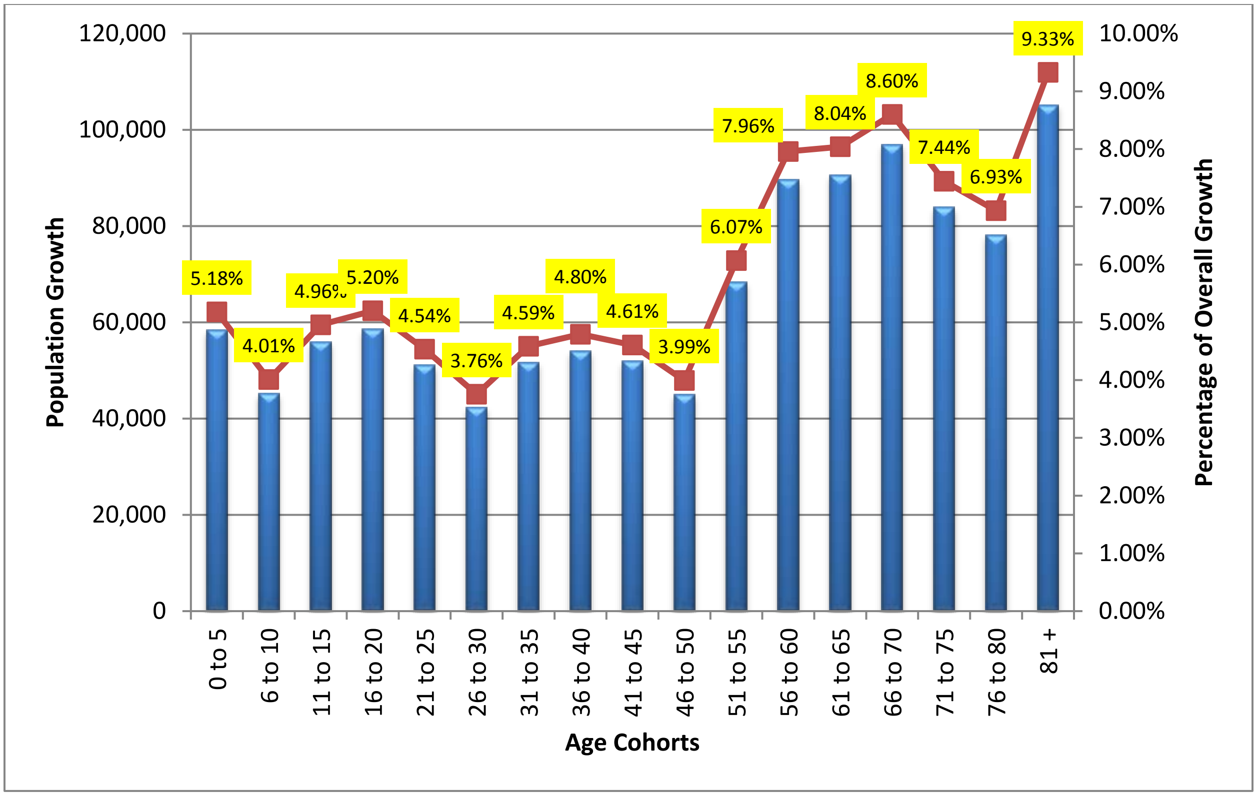


Figure 45. Austin-Area Population Growth Projections in Five-Year Increments (2010 to 2040).

Using four different National Highway Travel Survey (NHTS) year data, the average daily person trips by one-year age category can be plotted (*70*, *71*, *72*, *73*). Not surprisingly, the amount of VMT declines as a person ages. Might this change if vehicles were self-driving or could be called to deliver a person door to door?

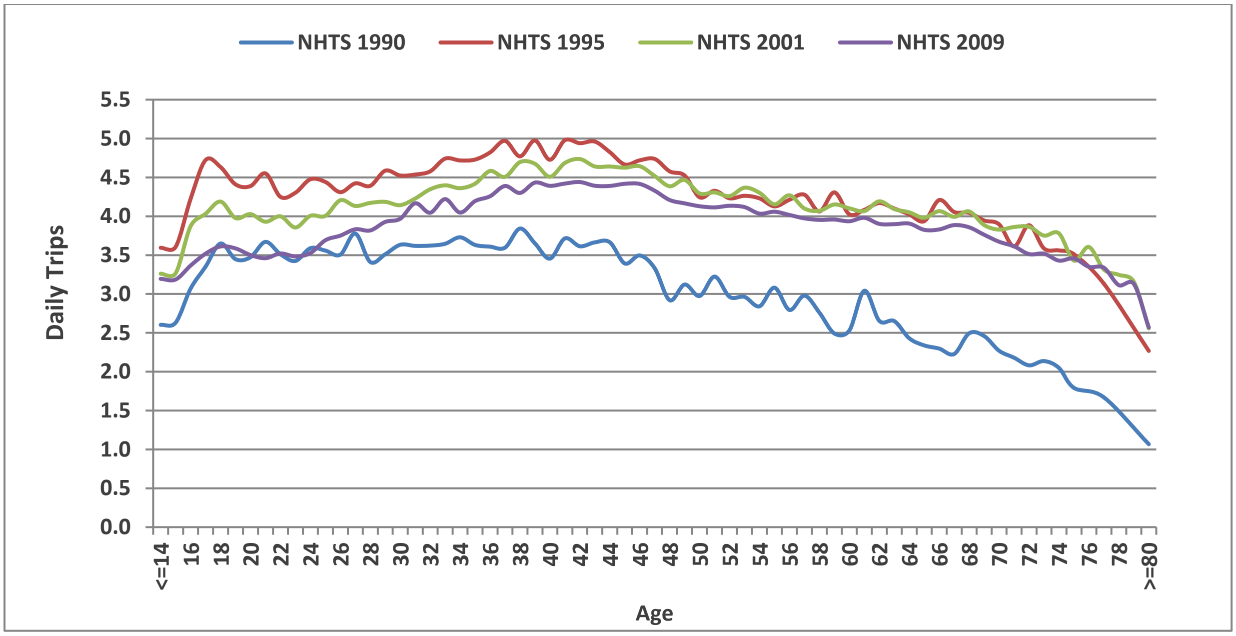


Figure 46. Changes in Person Trips by Age (*70–73*).

The 2008 Austin-area household travel survey was reprocessed using the 2015 household age and gender stratifications and 2040 household age and gender stratifications from TSDC to determine if the magnitude of overall change in travel could be measured using a different household stratification (with currently observed travel behavior). Researchers performed four separate analyses using the previous 2005–2006 household travel survey data that were collected to support the 2010 travel demand models. The survey was conducted in five counties because at the time, the CAMPO TDM had yet to incorporate Burnett County. The four scenarios are:

- **Scenario 1: 2015 Demographic/Age Stratification Total Trips**—This scenario is based on the 2015 household TSDC totals for the five-county region and the 2015 TSDC 0.5 population scenario by age/sex scenario.
- **Scenario 2: 2015 Demographic/Age Stratification Total Trips**—This scenario is based on the 2015 household TSDC totals for the five-county region and the 2040 TSDC 0.5 population by age/sex scenario.
- **Scenario 3: 2040 Demographic/Age Stratification Total Trips**—This scenario is based on the 2040 TSDC 0.5 population scenario (assuming that the 2015 average household size remains constant) for the five-county region and the product of the 2015 TSDC age/sex distributions to the 2040 TSDC 0.5 population control total.
- **Scenario 4: 2040 Demographic/Age Stratification Total Trips**—This scenario is based on the 2040 TSDC 0.5 population scenario (assuming that the 2015 average household size remains constant) and the product of the 2040 age/sex distributions to the 2040 TSDC 0.5 population control total.

Figure 47 illustrates the changes in person trips for each of the four scenarios by one-year age cohorts. In each instance, the total person trips declines past age 40, with the exception of Scenario 4, which remains relatively constant over age periods.

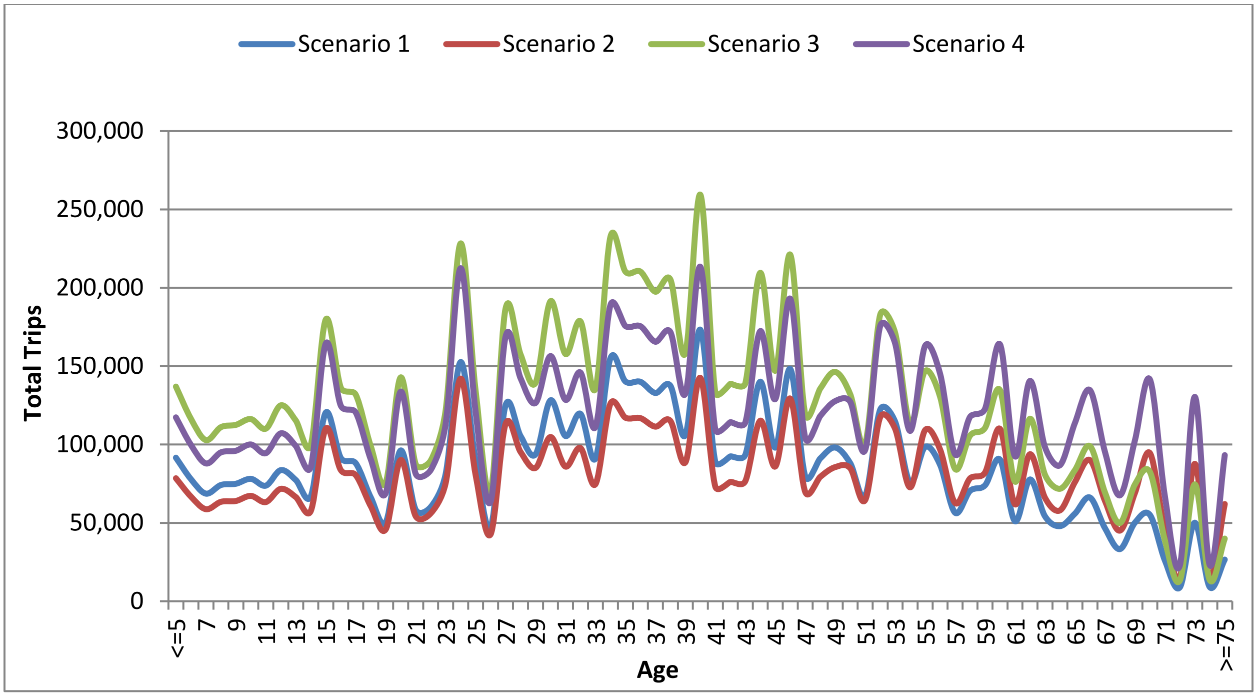


Figure 47. Changes in Person Trips (Austin Region) When Using Updated Age/Sex Distributions.

This analysis was rather inconclusive regarding the potential overall impacts that an aging population might have on overall travel if given greater access to mobility via autonomous and connected vehicles. Reprocessing the 2005–2006 household travel survey to either 2015 or 2040 household distributions actually resulted in an overall decline of approximately 0.5 percent total person trips and a slight increase of 1.5 percent total auto driver trips. The analysis, though, is based on historical and observed 2005 household travel data and does not capture behavioral changes that might occur in a fully autonomous environment where the household car might be able to drive a passenger or a vehicle could be called on demand. Table 14 shows the total travel changes when the existing 2005 household travel data are reanalyzed based on the 2015 and 2040 TSDC household age/gender stratifications.

Table 14. Changes in Person and Auto Driver Trip-Making Characteristics.

Year and Trip Type	2015 Age/Gender Stratification	2040 Age/Gender Stratification	Percent Difference
2015 Person Trips	7,293,465	7,252,653	−0.56%
2040 Person Trips	10,900,739	10,838,409	−0.58%
2015 Driver Trips	4,947,792	5,025,158	1.54%
2040 Driver Trips	7,392,338	7,505,952	1.51%

Rural Transit and On-Demand Services

As noted earlier, there are six different modes in the CAMPO mode choice models. Three different bus systems are operated by three separate agencies. These systems are the Texas State University (TSU) bus system that provides transit service to the city of San Marcos (south of Austin) and TSU; the Capital Area Rural Transportation System (CARTS), which provides on-demand, paratransit, and fixed bus service to rural regions in the CAMPO study area; and CapMETRO, which is the urban transit authority in the region. The TSU system has limited access to the city of Austin. The University of Texas also has a shuttle service that provides transit access to the campus from surrounding portions of the study area with predominant student housing. With respect to fixed-route transit systems, improved access to/from transit stops is a potential outcome of greater availability of on-demand vehicles (first mile/last mile) to satisfy these portions of tours. However, unless cost becomes an issue, it is not clear why a passenger would transfer from an autonomous vehicle to another system. Both CARTS and CapMETRO provide Americans with Disabilities Act (ADA) service for those with physical impairments.

On-demand transit service is also provided by CARTS. The CARTS service area also covers two additional counties that are outside of the six-county CAMPO MAB. Annual CARTS service ridership can be projected using the 2011–2015 growth rate, which is 1.90 percent. CARTS had a temporary spike in ridership in 2013 but has been decreasing the past two years. Table 15 shows the projected annual ridership numbers in 10-year increments.

Table 15. Projected CARTS Annual Ridership.

Year	Annual Ridership
2010	415,143
2020	576,768
2030	696,214
2040	840,398

Source: (*74*).

The data are based on annual boardings or unlinked passenger trips carried by CARTS. These data include medical transportation and other contracts that CARTS supplies. Since CARTS does not provide weekend service, the annual ridership numbers can be converted to daily weekday ridership. For 2040, this results in a little less than 3,200 daily trips. Expanding the urbanized area, though, will further reduce these estimates since CARTS service coverage will be further reduced. Consequently, since the six-county CAMPO region is expected to expand by 64 percent in terms of population, rural transportation service currently filled by CARTS may actually see a reduction through organic changes in urban form due to high population growth estimates.

It does not appear that either replacing on-demand transit service all together or augmenting it with on-demand connected taxis would greatly alter existing forecast traffic conditions. The level of population growth and continued urban expansion will measurably far outweigh any changes that might be brought about by replacing on-demand rural transit service with on-demand individual vehicles. Cost will probably play a far greater deterministic role as to whether on-demand services typically fulfilled by transit agencies will increase or decrease in the future once autonomous and connected vehicles are the standard. Transit agencies could conceivably continue to satisfy this role, but rather than employing drivers, they could deploy vehicles.

VMT of Zero-Occupant Vehicles

As mentioned earlier, four of the six scenarios presume that household vehicle ownership rates will continue to reflect current household vehicle ownership characteristics. Households will still acquire vehicles at the same rates, but these vehicles will replace human navigation through implementation of automation and connectivity innovations. It is possible that household vehicle ownership rates or the desire to continue to own and maintain individual cars will change. In this environment, all or some of the typical household trips could be replaced by on-demand, driverless automobiles. These vehicles are called robo-taxis.

Robo-taxis could replace the universe of vehicles on all facilities, or the operation of these types of vehicles could be limited to portions of the urbanized area (e.g., downtown). Transit trips or trips on other modes could potentially be satisfied with on-demand services that are realized as single-occupant vehicle trips (origin to destination) or that become part of a greater shared-ride route or tour. In none of the scenarios tested has the concept of driverless taxis that are circulating or traveling from point to point to pick up passengers (e.g., traveling salesman analogy) been adequately captured or reflected in system vehicle miles of travel. A seed matrix of trips could conceptually be created to be assigned to the network to arbitrarily create VMT, but ZOV trips would need to be proportional to the trips generated by household activity.

Although not tested in this study, a set of ZOV trips could be promulgated by factoring trip ends in trip tables produced by trip-based models. Parameters of ZOV trips would need to be assumed, such as trip origin. Theoretically, ZOVs would be connected to a centralized control system that would reposition the vehicle for optimal use for the next passenger call. In this way, estimates of ZOV trips could be made by area type since denser parts of an urban region will most likely require a greater number of AVs and market demand will require short response times for passenger pickup.

CHAPTER 6. TRAVEL BEHAVIOR SURVEY CONSIDERING THE IMPACT OF SELF-DRIVING VEHICLES

INTRODUCTION

Task 5 of the study involved conducting a web-based behavioral survey to explore the potential acceptance and impact of automated vehicle technology. To gather empirical evidence on these points, the research team adopted a 2015 self-driving vehicle survey that was developed by the research team for another TTI project. The 2015 survey was conducted in April–May 2015 and used an online sample provider, ResearchNow, targeting and recruiting potential respondents in the Austin region. A total of 556 usable responses were collected for the Austin region, which provided interesting background as a pilot study.

Appendix G contains the self-driving vehicle survey, which was composed of 36 questions. The survey was administered to individuals aged 18 years or older. The average response time was 10–15 minutes. The survey included several topics:

- Individual demographics (age, gender, etc.).
- Household demographics (income, number of children, etc.).
- Travel behavior characteristics (vehicle ownership, commute mode, etc.).
- Attitudes/perceptions toward self-driving vehicles and psychological variables (perceived safety, social influence, etc.).
- Personality scales (technology acceptance, desire for control, etc.).
- Some other potential factors (privacy concerns and adoption curve).

After approval from the TxDOT project team, and completion of the Institutional Review Board application, the self-driving vehicle survey was extended to the Houston, Dallas, and Waco regions using the same panel-provider platform as the Austin project. This new survey implementation took place in April–May 2016, just a year after the collection of the Austin sample. A total of 3,097 useable surveys were collected across three regions:

- Houston—1,532 survey responses.
- Dallas—1,039 survey responses.
- Waco—526 survey responses.

For comparison purposes, the data from the 2015 Austin sample are included in all statistics presented in this report. Adding different geographic content and including regions with different travel and demographic environments greatly helped to obtain more robust results and different insights on consumer acceptance and travel behavior impacts of self-driving vehicles, as presented in the different sections of this chapter.

Figure 48 shows a spatial distribution of the survey data for all four surveyed regions (i.e., Houston, Dallas, Waco, and Austin), and Table 16 and Table 17 present a summary of the demographics and travel behavior characteristics of the overall sample.

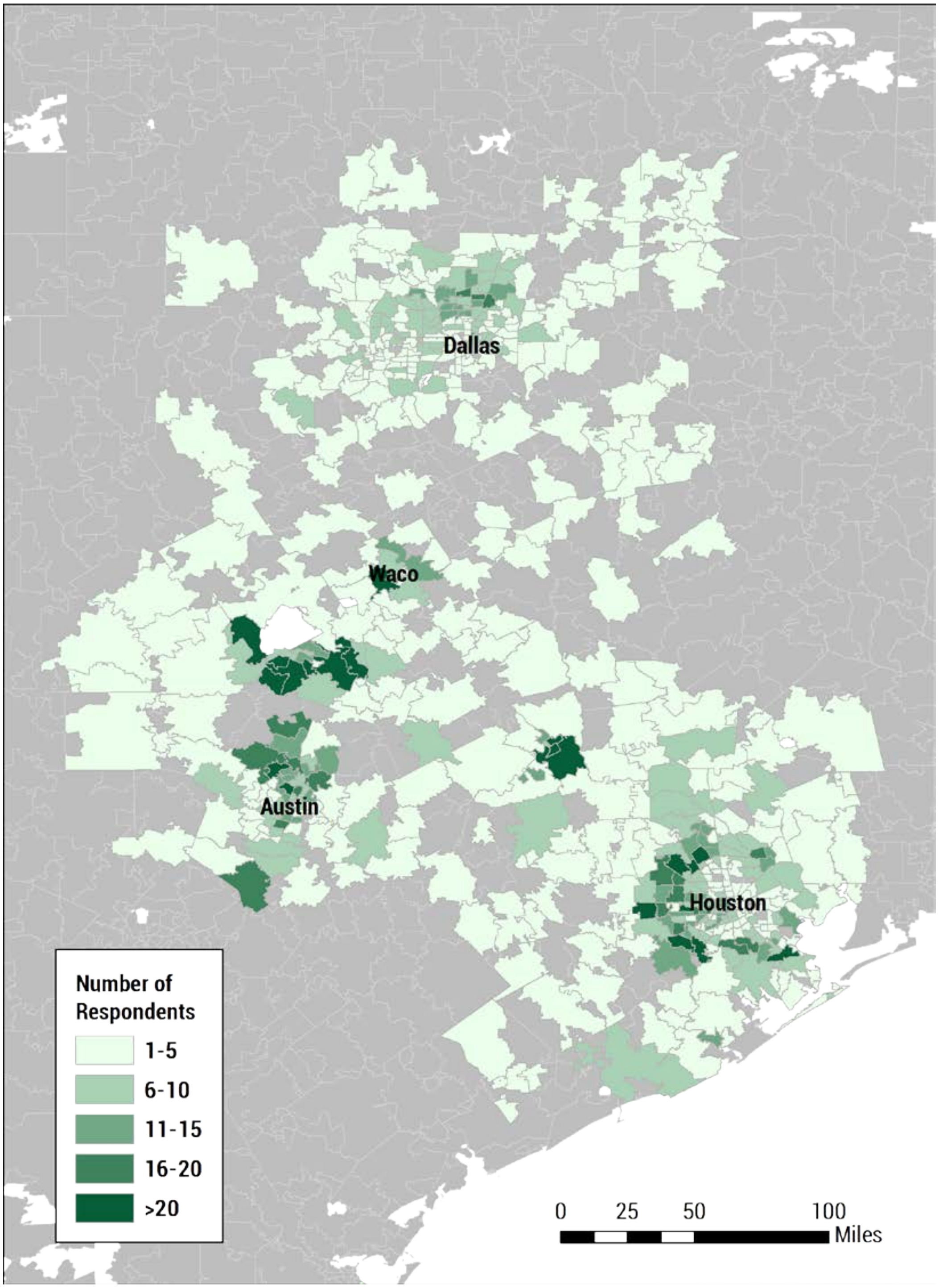


Figure 48. Spatial Distribution of Self-Driving Vehicle Survey Responses.

Table 16. Individual and Travel Behavior Characteristics of Survey Participants.

N (Total Sample Size) = 3653	Houston	Dallas	Waco	Austin
	N=1532	N=1039	N=526	N=556
Age				
Less than 30 years old	26.5%	25.0%	26.2%	23.7%
30 and 45 years old	26.2%	29.2%	25.3%	27.9%
46 and 65 years old	23.4%	23.5%	28.1%	30.0%
Greater than 65 years old	24.0%	22.3%	20.3%	18.3%
Gender				
Female	51.5%	50.3%	46.6%	42.1%
Male	48.2%	49.5%	53.4%	57.9%
Other	0.3%	0.2%	0.0%	0.0%
Education				
Grade 12 or less	1.8%	1.4%	2.9%	2.0%
High school graduate	12.7%	13.1%	17.3%	10.1%
Associate’s degree or some college	26.3%	25.4%	30.0%	20.1%
Bachelor’s degree	35.2%	37.5%	24.9%	41.2%
Higher than bachelor’s degree	24.1%	22.5%	24.9%	26.6%
Employment				
Employed full-time	52.1%	52.9%	48.7%	51.6%
Employed part-time	10.8%	11.6%	12.4%	12.6%
Not currently employed	11.9%	12.3%	15.4%	8.3%
Retired	25.2%	23.1%	23.6%	27.5%
Student				
Full-time student	9.9%	9.3%	12.5%	7.4%
Part-time student	6.3%	4.8%	5.5%	4.9%
Not a student	83.9%	85.9%	81.9%	87.8%
Licensed driver				
Yes	96.1%	95.2%	96.0%	97.5%
No	3.9%	4.8%	4.0%	2.5%
Physical condition preventing driving				
Yes	1.6%	2.3%	0.6%	2.0%
No	98.4%	97.7%	99.4%	98.0%
Own or lease a vehicle				
Yes	93.2%	92.1%	93.2%	94.2%
No	6.8%	7.9%	6.8%	5.8%
Own or lease a vehicle with automated features (N=524)				
Yes	35.3%	32.2%	29.6%	26.1%
No	64.7%	67.8%	70.4%	73.9%

.

Table 16. Individual and Travel Behavior Characteristics of Survey Participants (Continued).

N (Total Sample Size) = 3653	Houston	Dallas	Waco	Austin
	N=1532	N=1039	N=526	N=556
Commute mode last week (N=2312)				
Vehicle driver	87.5%	85.7%	92.2%	85.2%
Vehicle passenger	3.2%	4.0%	2.5%	4.8%
Public transit	3.2%	3.6%	1.9%	5.9%
Walk	1.8%	1.0%	0.6%	0.8%
Bike	0.4%	1.3%	1.2%	0.0%
Telecommute (work at home)	3.8%	4.3%	1.6%	3.4%
School mode last week (N= 557)				
Vehicle driver	63.2%	55.8%	57.9%	50.0%
Vehicle passenger	13.0%	15.6%	5.3%	4.4%
Public transit	4.9%	8.2%	7.4%	19.1%
Walk	6.9%	8.2%	11.6%	10.3%
Bike	2.0%	2.0%	6.3%	1.5%
Telecommute (work at home)	10.1%	10.2%	11.6%	14.7%
Frequency of motor vehicle driving				
Every day	74.6%	73.9%	73.2%	73.6%
A few days a week	19.2%	17.6%	20.2%	20.1%
A few days a month	2.9%	3.8%	3.4%	2.5%
Almost never	3.3%	4.6%	3.2%	3.8%
Miles driven in 2014				
Less than 5,000	15.1%	16.0%	16.5%	15.6%
5,000 to 10,000	32.1%	31.5%	26.4%	34.4%
10,000 to 15,000	32.2%	31.7%	28.5%	34.9%
More than 15,000	20.5%	20.9%	28.5%	15.1%
Transportation services used last week				
Carsharing services, like Zipcar or Car2Go	2.6%	2.2%	1.3%	1.4%
Ridesharing services, like Carma, Carpooling, or Ridejoy	1.4%	1.5%	1.5%	1.1%
Taxi services, like Uber or Yellow Cab	11.7%	12.9%	8.0%	7.7%
Transportation apps, like Waze, Roadify, Google Maps	25.1%	24.7%	23.6%	26.6%
Public transit services, either bus or rail	7.8%	8.4%	6.1%	13.8%
Transportation service for senior or disabled	0.7%	1.0%	1.3%	0.7%
None of the above	63.8%	62.1%	68.1%	62.2%

Table 17. Household Characteristics of Survey Participants.

N (Total Sample Size) = 3653	Houston	Dallas	Waco	Austin
	N=1532	N=1039	N=526	N=556
Household size				
One	20.6%	19.7%	15.2%	18.9%
Two	42.4%	43.8%	44.5%	49.5%
Three	16.1%	16.1%	17.1%	14.4%
Four or more	20.9%	20.4%	23.2%	17.3%
Number of kids less than 16 years old				
None	74.9%	74.4%	71.7%	79.1%
One	12.6%	11.8%	12.9%	10.3%
Two	8.6%	9.9%	10.5%	7.0%
Three or more	3.9%	3.8%	4.9%	3.6%
Number of motor vehicles in the household				
None	3.2%	4.1%	2.7%	2.3%
One	29.4%	28.4%	28.3%	27.3%
Two	48.6%	49.0%	45.4%	48.4%
Three or more	18.8%	18.5%	23.6%	21.9%
Household income for the last year (N=3647)				
Less than $25,000	9.2%	9.5%	13.3%	11.0%
$25,000 to $49,999	19.8%	20.2%	24.4%	21.6%
$50,000 to $99,999	38.4%	38.4%	37.0%	37.4%
$100,000 to $149,999	19.9%	21.2%	16.2%	18.0%
$150,000 or more	12.8%	10.8%	9.1%	12.1%

INTENT TO USE SELF-DRIVING VEHICLES

As the primary interest of this study, survey respondents were asked about their intent to use self-driving vehicles.

The survey asked the questions on intent to use after providing a definition of self-driving vehicles, followed by a link to a short video on self-driving vehicles:

> *In our study, we are interested in your opinions about self-driving vehicles. You may be able to buy a self-driving vehicle from major manufacturers or access one through a car-sharing service within the next 5-8 years. A self-driving vehicle is a vehicle that controls all driving functions for an entire trip, including steering, braking, and acceleration. It covers freeway driving, neighborhood driving, and activities like parking. The "operator" provides destination or navigation input, and is in the vehicle to take over control of the vehicle if conditions warrant. The market push for self-driving vehicles is to make driving safer and more efficient.*

Please watch the following video on self-driving vehicles before continuing with the next questions.

Following the video, respondents were asked if they had heard of self-driving vehicles before participating in the survey. The majority of respondents had heard of self-driving vehicles, with relatively similar levels for Houston (85 percent), Dallas (84 percent), and Waco (84 percent), and a slightly lower percentage for Austin (80 percent), which might be indicative of the one-year difference between the Austin survey (conducted in 2015) and the remaining region survey (conducted in 2016).

After answering several questions about their attitudes toward self-driving vehicles, respondents were asked about their intent to use:

Imagine that self-driving vehicles were on the market now for either purchase or rental. What is the likelihood that you would ride in a self-driving vehicle for everyday use?

The following sections discuss the distribution of answers regarding intent to use.

Four-Level Segmentation of Intent to Use

Figure 49 suggests a fairly consistent distribution with regard to intent to use self-driving vehicles across all cities, with most surveyed people in a wait-and-see mode (somewhat likely or somewhat unlikely) and with smaller segments of the population sampled at the intense end of the spectrum (extremely likely or extremely unlikely). Interestingly, the new surveyed regions (i.e., Houston, Dallas, and Waco) indicated a slightly higher level of intention to use compared to the Austin sample, which had an even a split of intent to use (50 percent indicating an intent to use and 50 percent indicating an intent not to use). Among all regions, Dallas had the highest percentage of intent to use (56 percent), followed by Houston (54 percent), and Waco (53 percent). This increase might be related to an increased awareness of self-driving vehicles over the last year, after the implementation of the Austin survey. As indicated in Zmud et al. (*75*), as people are more aware of or educated about automated or connected vehicles, the acceptance rates are expected to increase. On the other hand, the results might also be an indication of different travel environments and demographic characteristics of the populations residing in different cities, as discussed in the remainder of the chapter.

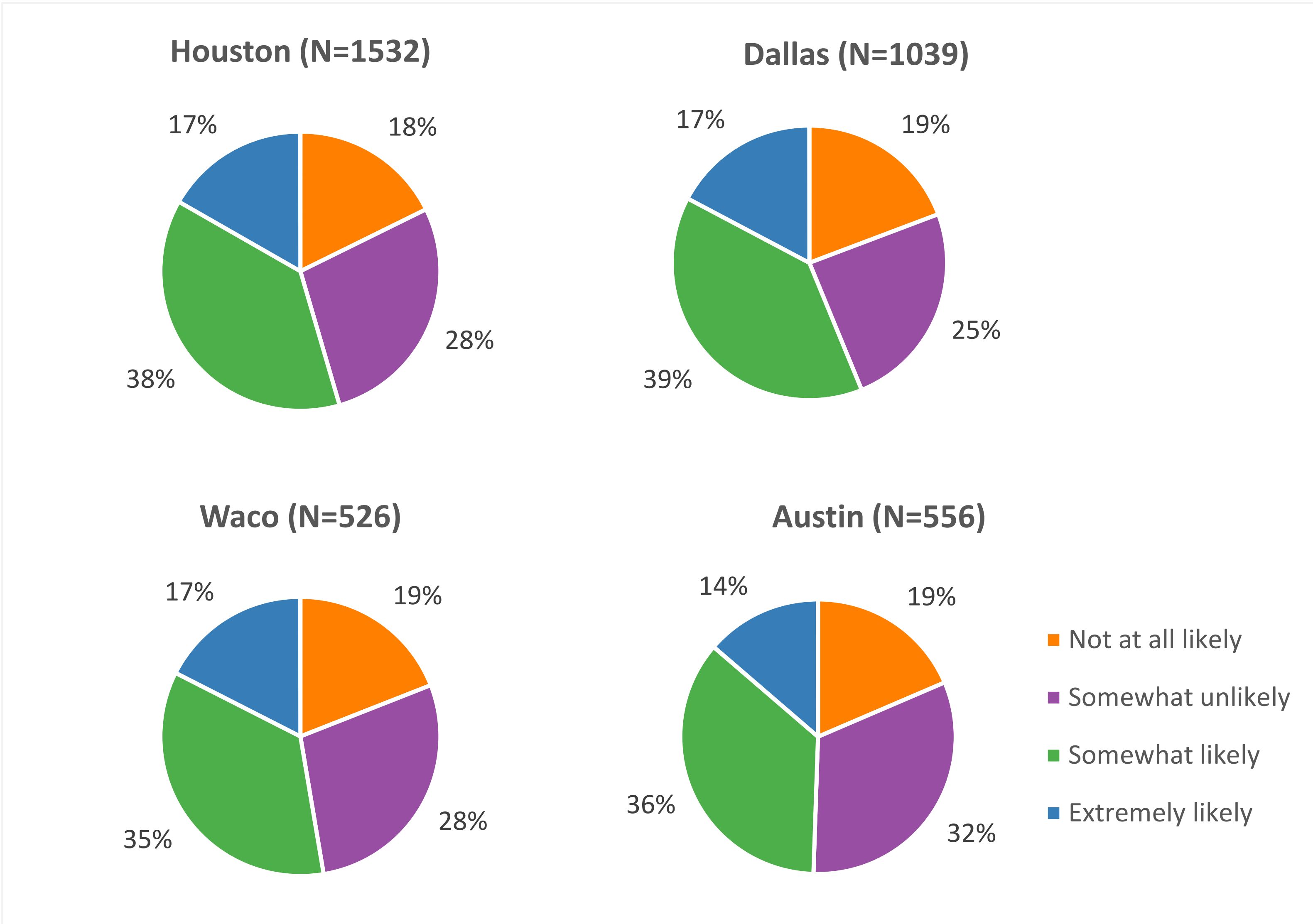


Figure 49. Intent to Use Self-Driving Vehicles.

Reasons for Not Intending to Use Self-Driving Vehicles

Respondents who indicated an unwillingness to use self-driving vehicles were also asked about their reasoning. As seen in Figure 50, the results highlighted the lack of trust in the technology as the most frequently mentioned reason for being unlikely to ride in self-driving vehicles for everyday use across all regions (44 percent in Waco, and 42 percent each for the remaining regions). This reason was followed by safety (with more emphasis in Houston and Dallas) and cost (with more emphasis in Waco and Austin). Although at a much lower level relatively, liking to drive or desire for vehicle control was another reason for not intending to use self-driving vehicles, with the highest rate in Austin (9 percent). Some individuals also mentioned that they did not see a need to use these types of vehicles as long as they had the ability to drive.

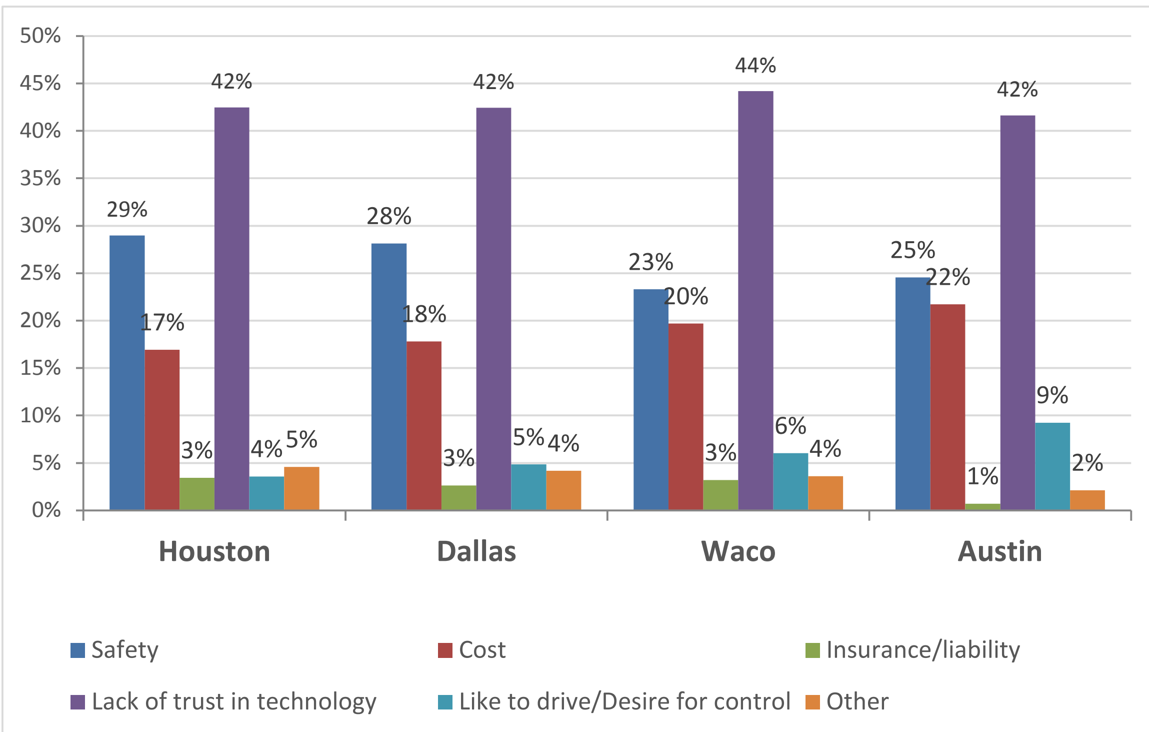


Figure 50. Reasons for Not Intending to Use Self-Driving Vehicles.

Data privacy and technology adoption were further investigated for their potential influence on intent to use self-driving vehicles.

Effect of Data Privacy and Technology on Intent to Use

Data Privacy

Table 18 presents data privacy concerns of the surveyed population, suggesting no significant variations across cities. In Austin and Waco, a slight majority of respondents had more concerns about using online technologies in most or all situations (51 percent and 53 percent, respectively), while the corresponding numbers decreased to 49 percent in Houston and

47 percent in Dallas. Respondents indicating no concerns across the sample ranged from 5 to 8 percent across different regions, with Dallas being the least sensitive and Austin being the most sensitive. Individuals who had concerns at almost all times were consistently around 14 percent for all regions.

Table 18. Data Privacy Concerns.

Data Privacy Concern	Houston	Dallas	Waco	Austin
Not at all concerned	6.5%	7.9%	6.5%	5.0%
Somewhat concerned (in some situations)	44.3%	44.7%	40.84%	44.1%
Moderately concerned (in most situations)	35.7%	33.7%	38.6%	37.4%
Extremely concerned (in all situations)	13.4%	13.7%	14.1%	13.5%
Total	100.0%	100.00%	100.00%	100.00%

Looking at the correlation between data privacy and intent to use, in general, the higher the level of data privacy concerns, the less likely a person was to use self-driving vehicles in Houston, Waco, and Austin. However, the results from Dallas did not follow this consistent trend, leading to inconclusive findings. Some variations were also observed across cities, as presented in Figure 51.

For example, in Houston, no major differences were observed across different categories of privacy concern, with a slight majority being more likely to use in general. In Waco, of those who expressed few privacy concerns, 57 percent were more likely to use self-driving vehicles, while of those who expressed more privacy concerns, the percentage of likelihood decreased to 49 percent. Similar trends were also seen for Austin, though the numbers were more extreme. Of those who expressed no data privacy concerns, a considerably high percentage (71 percent) were likely to use self-driving vehicles. Similarly, of those who expressed concerns in all situations, a relatively higher percentage (60 percent) were unlikely to use self-driving vehicles.

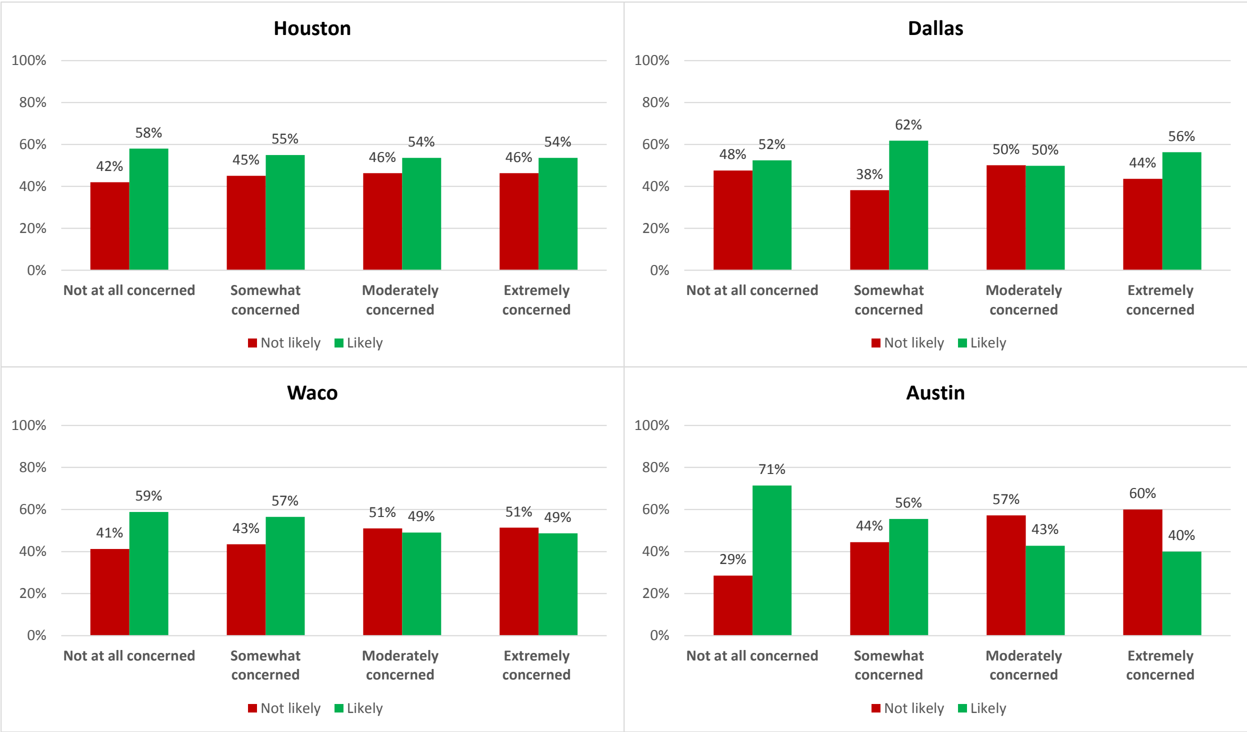


Figure 51. Intent to Use by Data Privacy Concerns.

Technology Adoption

The adoption level was characterized in three levels: (a) early adopters, who are among the first to adopt new technology; (b) late adopters, who wait awhile before adopting new technology; and (c) laggards, who are among the last to adopt new technology if they adopt at all. Table 19 and Table 20 present technology adoption levels of the population by geographic area and age category, respectively.

A majority of the sample considered themselves as late adopters on the technology adoption curve across all regions (ranging from 60 to 66 percent). Although Austin is considered a technology hub, early adopters were more prevalent in other regions, with Houston being at the top (29 percent), followed by Dallas (27 percent). Laggards compromised a lower percentage of the overall sample, with similar trends across different regions (12 to 13 percent).

Age was related to the adoption curve and was consistent across all regions, with the largest proportion of early adopters in the younger age group (less than or equal to 45 years of age) and the largest proportion of laggards in the older age group (greater than 45 years of age).

Table 19. Technology Adoption by Geographic Area.

Adoption Curve	Houston	Dallas	Waco	Austin
Early adopter	28.7%	27.2%	25.3%	21.2%
Late adopter	59.7%	60.4%	61.4%	65.7%
Laggard	11.6%	12.3%	13.3%	13.1%
Total	100.0%	100.0%	100.0%	100.0%

Table 20. Technology Adoption by Age.

Geographic Area	Adoption Curve	Less Than 30 Years Old	Between 30 and 45 Years Old	Between 46 and 65 Years Old	Greater Than 65 Years Old	Total
Houston	Early adopter	36.4%	32.6%	19.4%	11.6%	100.0%
	Late adopter	23.8%	25.2%	24.0%	26.9%	100.0%
	Laggard	15.7%	15.2%	29.8%	39.3%	100.0%
Dallas	Early adopter	36.0%	39.6%	15.5%	8.8%	100.0%
	Late adopter	22.0%	26.1%	26.0%	26.0%	100.0%
	Laggard	15.6%	21.1%	28.9%	34.4%	100.0%
Waco	Early adopter	37.6%	30.8%	18.8%	12.8%	100.0%
	Late adopter	22.9%	23.2%	30.7%	23.2%	100.0%
	Laggard	20.0%	24.3%	34.3%	21.4%	100.0%
Austin	Early adopter	31.4%	32.2%	24.6%	11.9%	100.0%
	Late adopter	23.0%	27.7%	30.7%	18.6%	100.0%
	Laggard	15.1%	21.9%	35.6%	27.4%	100.0%

When intent to use was disaggregated by the adoption curve, the results were expected and consistent across different regions (see Figure 52). Early adopters skewed heavily toward intent to use (71 percent in Houston and Dallas, 69 percent in Waco, and 65 percent in Austin), whereas laggards skewed toward not using (68 percent in Houston, 66 percent in Dallas and Waco, and 62 percent in Austin). The small number of laggards who were extremely likely to use self-driving vehicles tended to be younger than 30.

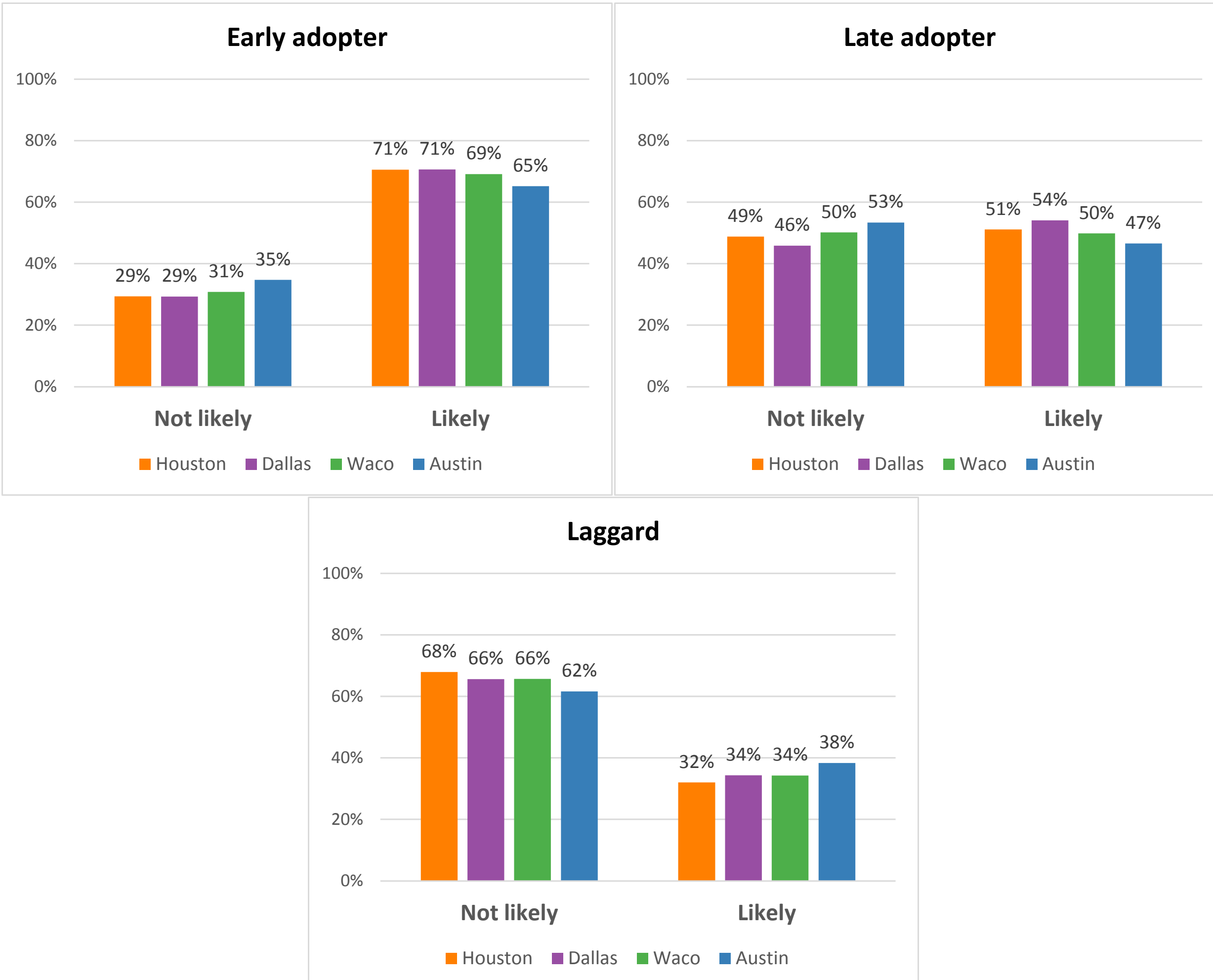


Figure 52. Intent to Use by Technology Adoption.

Intent to Use by Respondents' Characteristics

Individual Demographics

Age. Intent to use was explored by several individual demographics. In terms of age, while the Austin sample indicated that a respondent's age was not predictive of intent to use self-driving vehicles, age was much more influential for Houston and Dallas (see Figure 53 and Figure 54).

As seen in Figure 53, for all regions, intent to use was almost evenly split for people greater than 65 years old, and the distribution was slightly uneven for people 46 to 65 years old. On the other hand, for Houston and Dallas, the distribution was quite skewed for younger people. A majority of people residing in Houston and under 46 years old were more likely to use self-driving vehicles (58 percent). The youngest respondents from Dallas (less than 30 years old) had the highest percentage of intention to use (65 percent), followed by people 30–45 years old (60 percent). A similar higher likelihood of intent to use was also observed for Waco respondents aged 30–45 years old (59 percent).

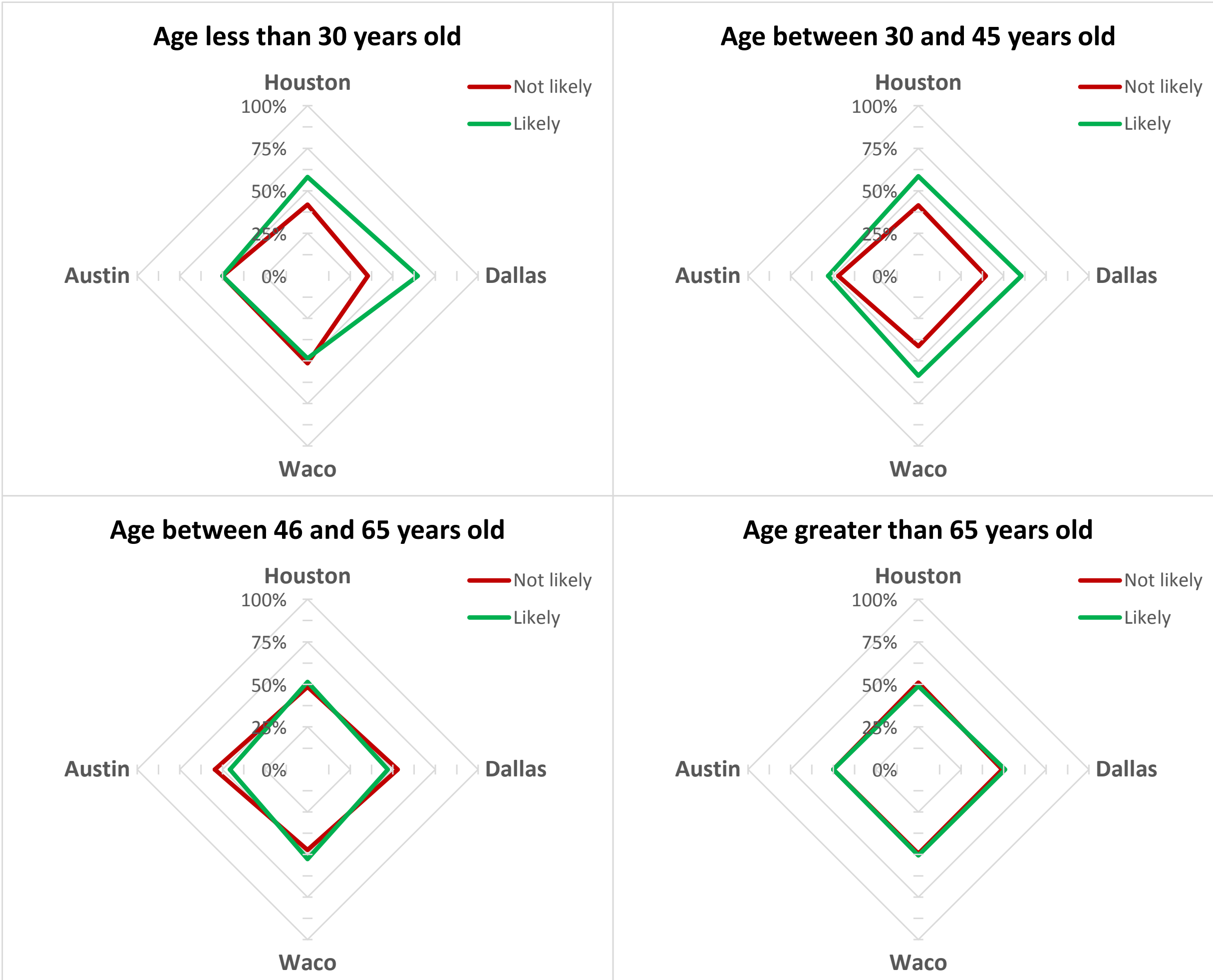


Figure 53. Intent to Use by Age.

Figure 54 provides more details on the youngest and oldest population groups, with their intention to use segmented at four levels. Compared to other regions, Austin had the highest percentage of respondents under 30 years old who indicated being not at all likely to use self-driving vehicles (23 percent), as well as the lowest percentage of the same age group being extremely likely to use (11 percent). On the other hand, individuals older than 65 residing in Austin had the lowest rate of being rejecters (i.e., not at all likely) for using self-driving vehicles (15 percent), but also the highest rate of staying in a wait-and-see period (35 percent were somewhat unlikely, while 36 percent were somewhat likely).

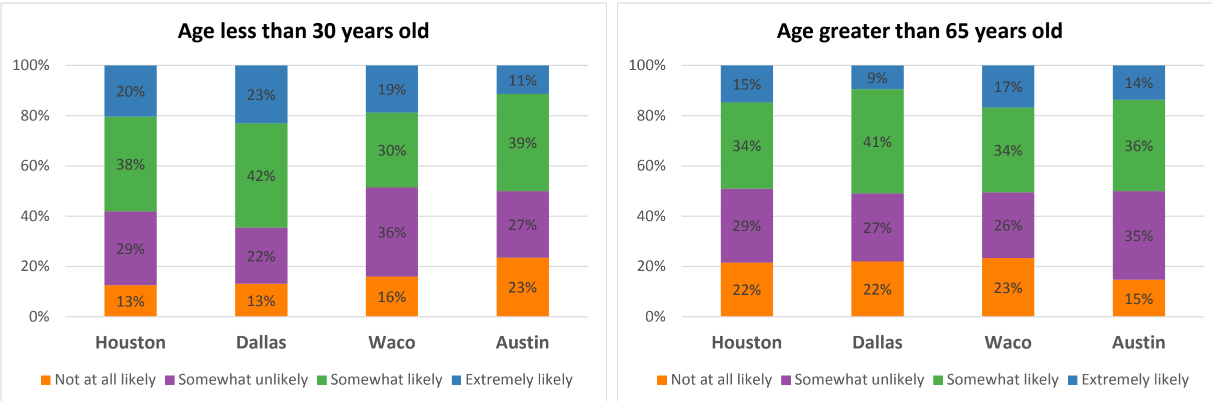


Figure 54. Intent to Use by Youngest and Oldest Age Categories.

Gender. Figure 55 presents intent to use by gender. Interestingly, males, compared to females, had a more consistent tendency toward being likely to use self-driving vehicles. There were more fluctuations among females across different regions regarding intention to use. Gender differences were observed across all regions except Dallas, which indicated similar distributions of intent to use, with 44 percent unlikely and 56 percent likely for both females and males. In Houston, females had an equal split, while males (58 percent) were slightly more likely to use self-driving vehicles compared to females (50 percent). In Waco, females were more likely to use self-driving vehicles than males, while the reverse relationship was observed in Austin.

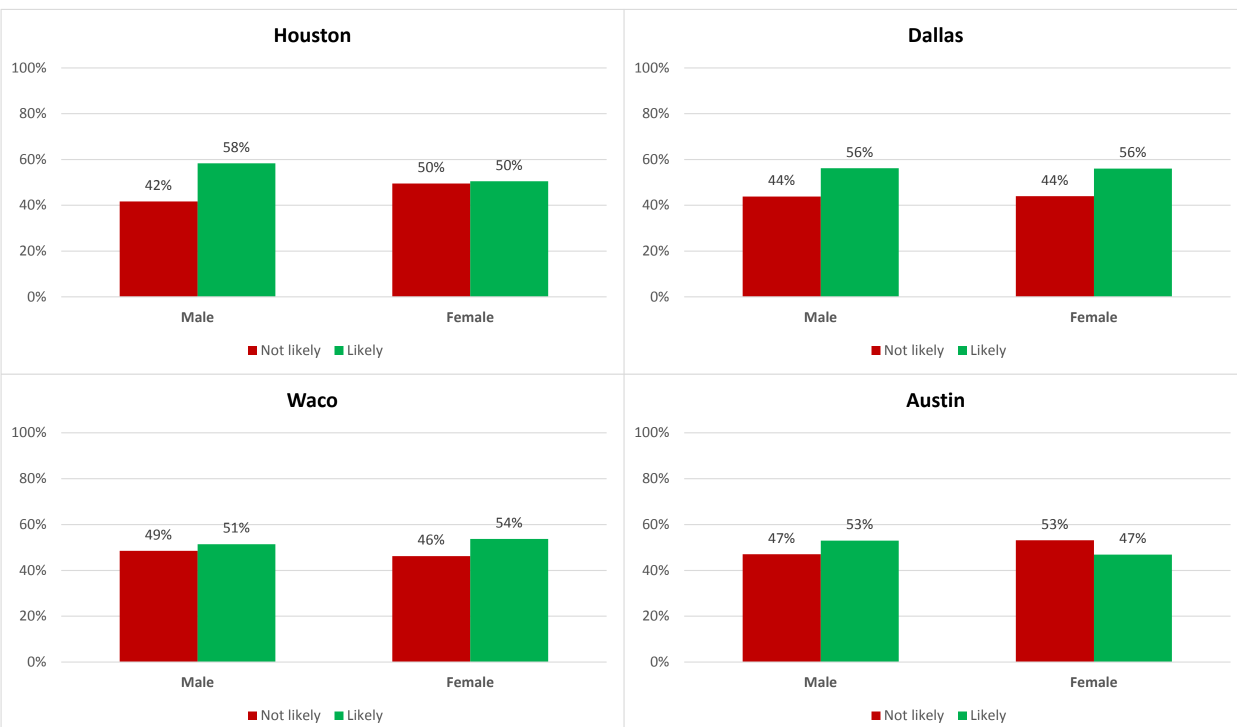


Figure 55. Intent to Use by Gender.

Education. In terms of educational attainment, the results did not show substantial differences among different regions (see Figure 56). In general, there was a slight increase in intent to use among individuals with higher educational levels. Austin, however, provided a more special case. Specifically, respondents with an education level of Grade 12 or less were significantly more enthusiastic about using self-driving vehicles, with no rejecters (i.e., not at all likely) and more than 80 percent being in favor of using (45 percent somewhat likely, 36 percent extremely likely).

Figure 56. Intent to Use by Education.

Employment and student status. Few insights were observed regarding employment levels (see Figure 57). Overall, full-time employed individuals were more likely to use self-driving vehicles, while retirees were indifferent about their choice of intent to use. In Austin, part-time employees and unemployed individuals were more unlikely to use self-driving vehicles (around 58 percent each). In addition, residents of Waco had the smallest differences in their intent to use across employment categories.

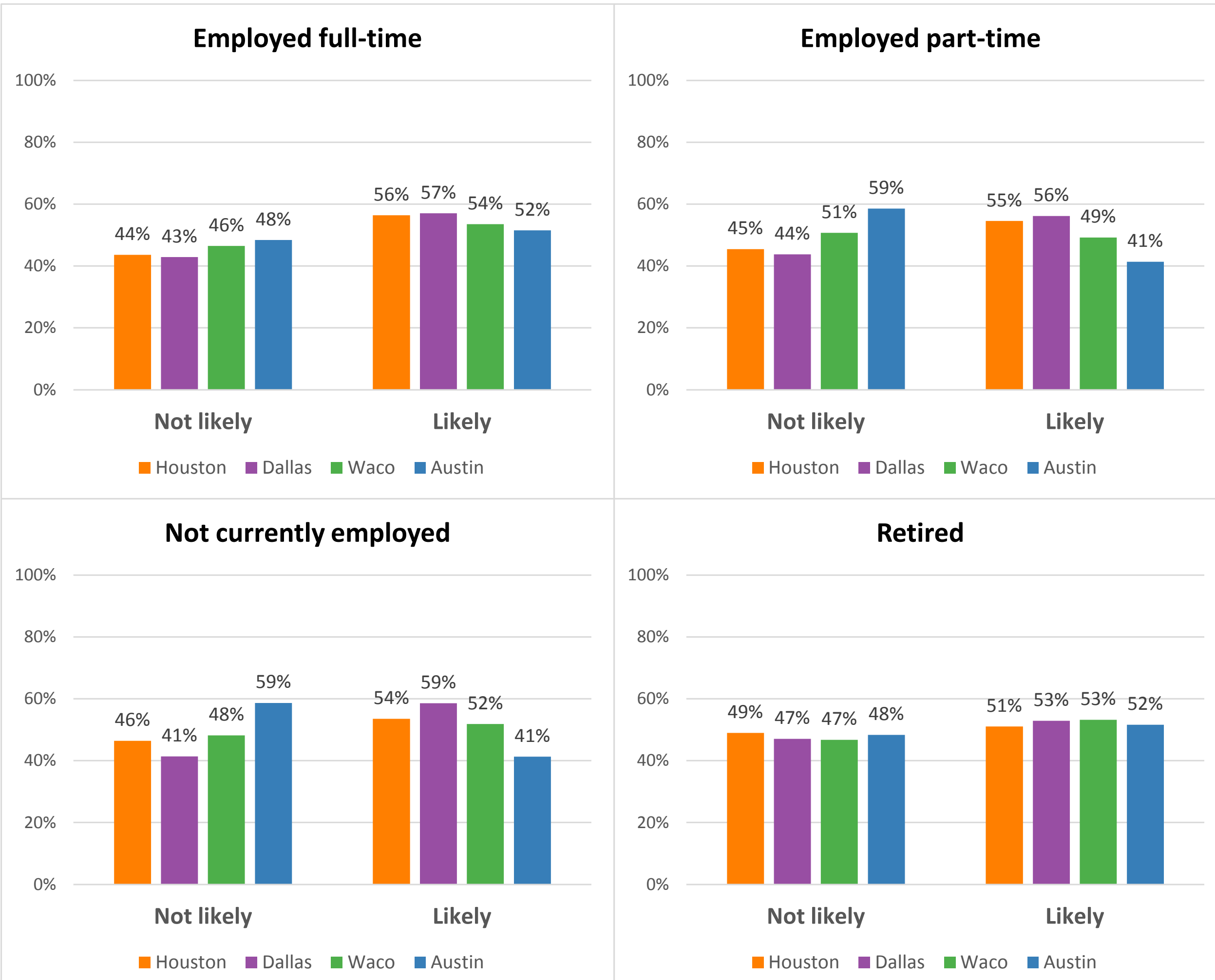


Figure 57. Intent to Use by Employment.

Finally, as Figure 58 shows, a strong majority of full-time students residing in Houston or Dallas reported being more likely to use self-driving vehicles. Being a part-time student had a similar effect in those regions, though the effect size was smaller, especially for Houston.

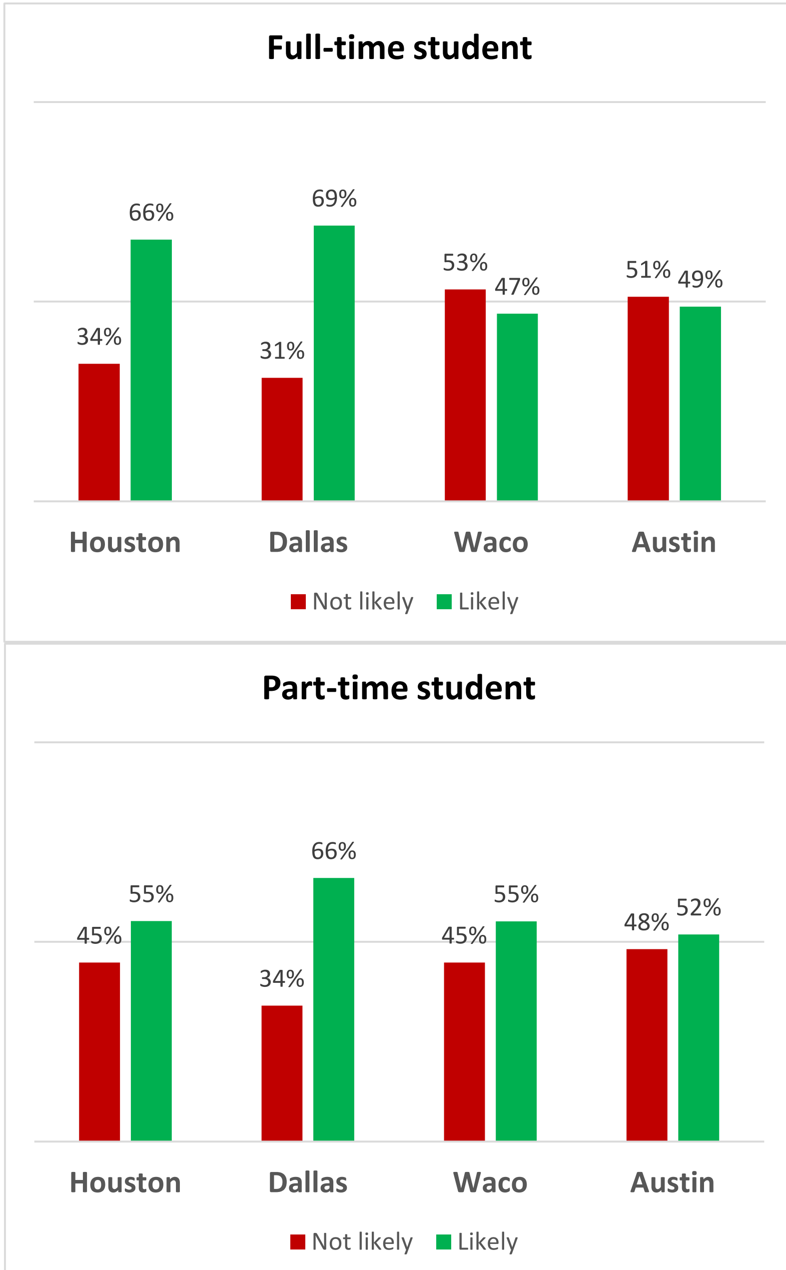


Figure 58. Intent to Use by Student Status.

Household Demographics

Income. Figure 59 presents the household income effects. The results showed inconsistent income effects across the regions. For instance, two-thirds of Waco residents with a household income of more than $150,000 were likely to use self-driving vehicles, with the lowest segment of rejecters (8 percent). In Houston, income had a positive impact on intent to use among individuals with incomes less than $100,000, whereas the intent to use decreased among individuals with a household income of more than $100,000. In Dallas, income had no major effect on intent to use, and in Austin, a fluctuating trend was observed across different income categories.

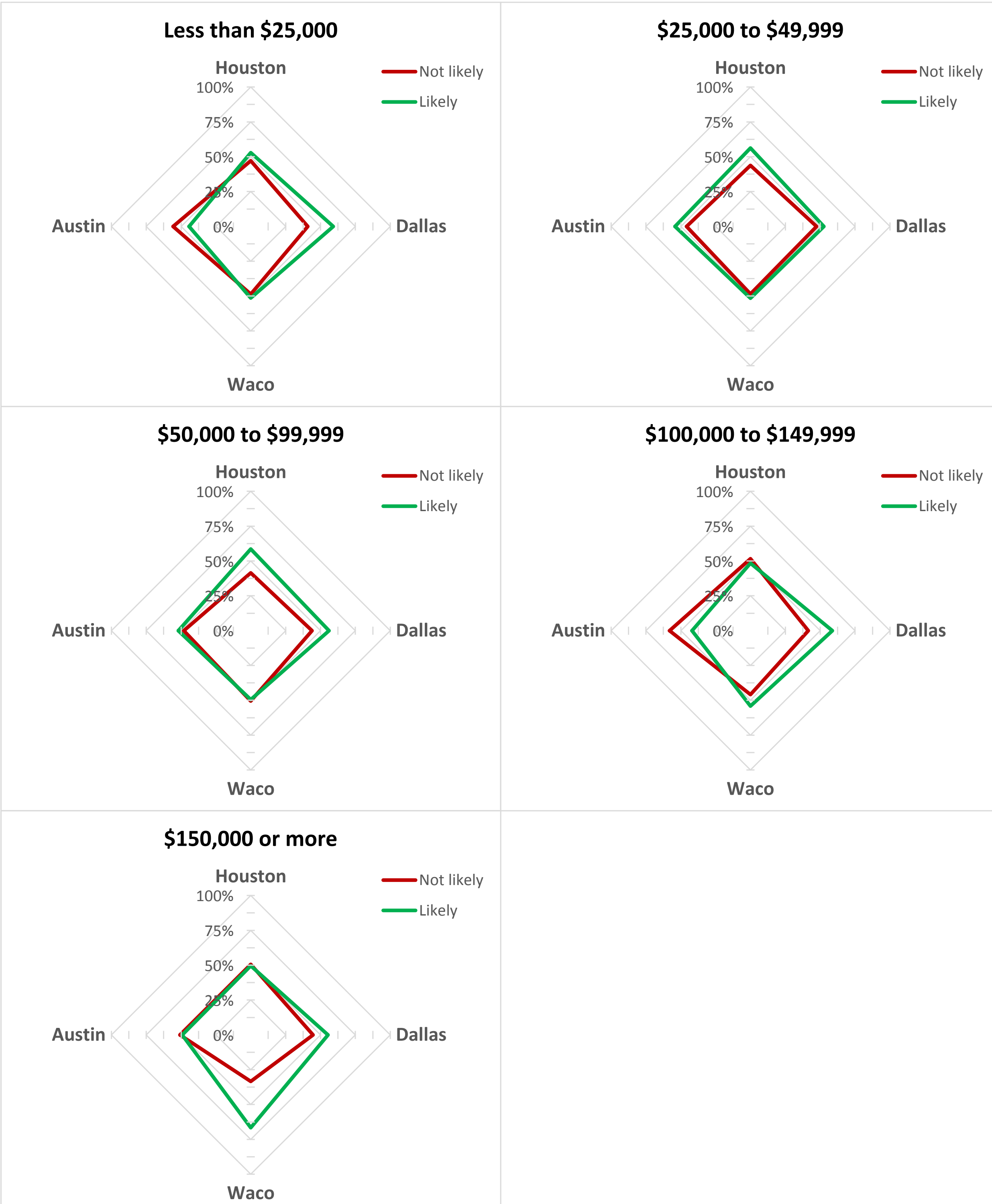


Figure 59. Intent to Use by Household Income.

Number of children. As seen in Figure 60, the presence of children in the household was associated with intent to use. Except in Austin, households with children were more likely to have an intention toward using self-driving vehicles than households without children: Houston—59 percent versus 53 percent; Dallas—56 percent versus 54 percent; and Waco—58 percent versus 51 percent. In Austin, the association was reversed, with households with children being less likely to use self-driving vehicles than households without children (45 percent versus 51 percent). However, the results consistently pointed to a higher likelihood of intent to use in all regions for households with more than three children. Interestingly, over one-third of the 20 households in the Austin sample with three or more children were extremely likely to use self-driving vehicles, a higher percentage than in any other region.

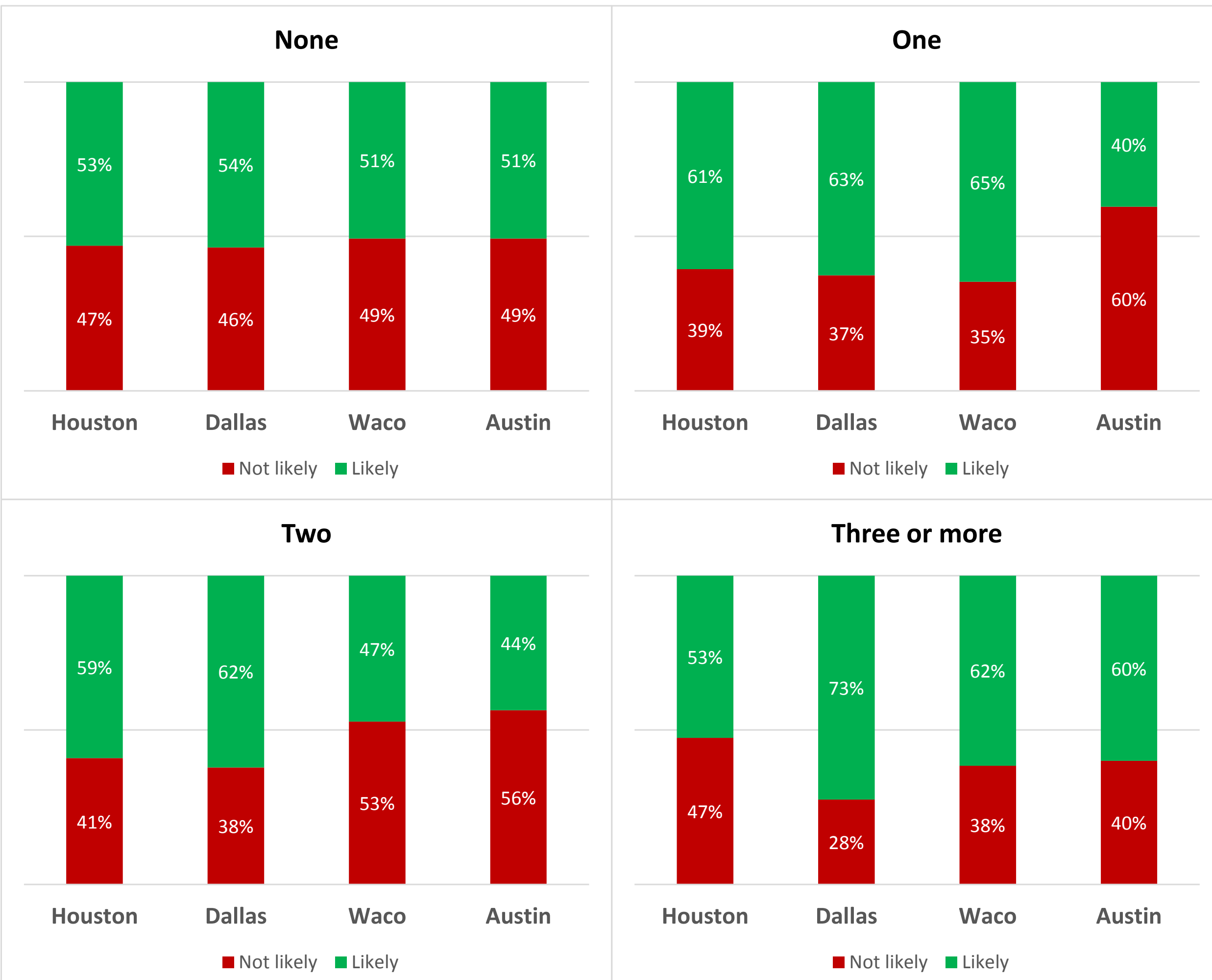


Figure 60. Intent to Use by Number of Children in the Household.

Travel Behavior Characteristics

Driving condition. Having a driver's license had a significant effect on intent to use. Individuals without a driver's license indicated a higher likelihood of intent to use than did individuals with a driver's license. This higher tendency in intent to use was consistent across all regions: 67 percent in Houston, 76 percent in Dallas, 62 percent in Waco, and 71 percent in Austin (see Figure 61). This effect was more pronounced for respondents with physical conditions that prevented driving, as shown in Figure 62.

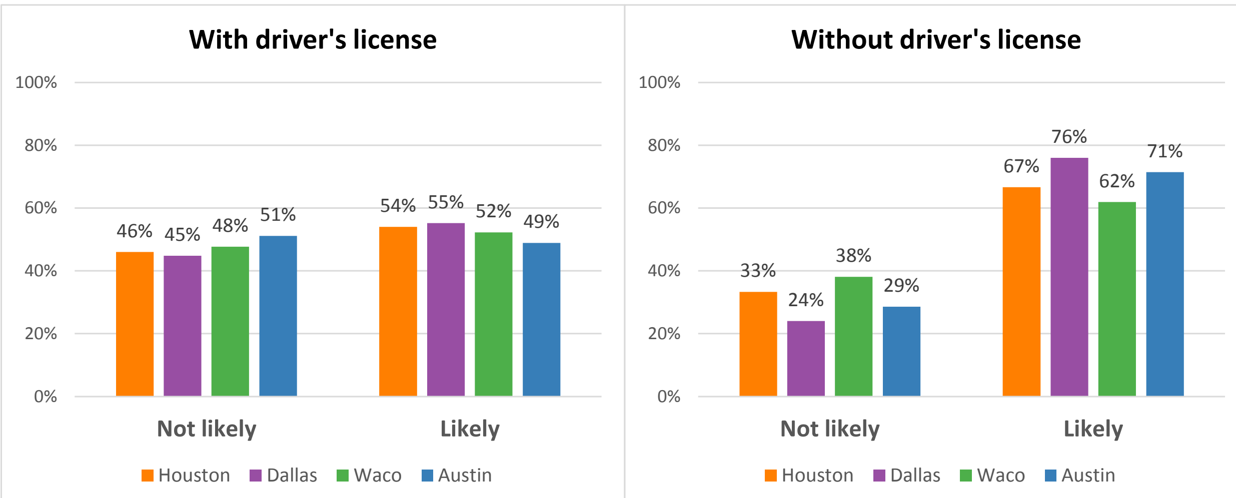


Figure 61. Intent to Use by Driver License.

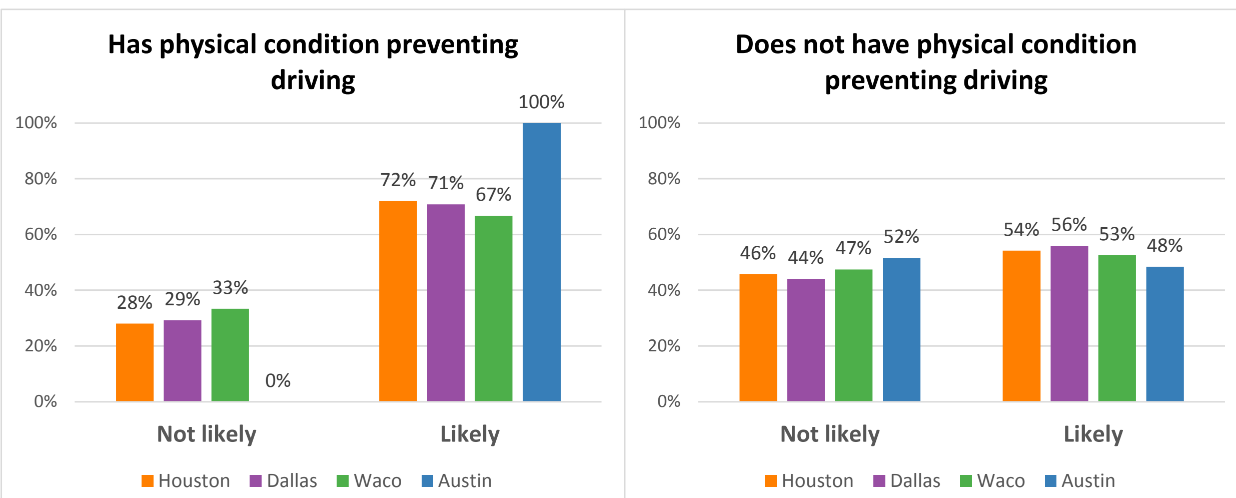


Figure 62. Intent to Use by Physical Condition Preventing Driving.

Vehicle ownership. Currently owning or leasing a vehicle had no effect on people's intent to use in Waco and Austin. However, in Houston and Dallas, individuals who did not currently own or lease a vehicle were more inclined to use self-driving vehicle (62 percent each) than those who owned or leased a vehicle (54 and 56 percent, respectively). On the other hand, the results suggested a consistently higher tendency to use self-driving vehicles if individuals currently owned or leased a vehicle with highly automated features (ranging from 57 to 63 percent for each region). Figure 63 and Figure 64 provide the details on vehicle ownership results.

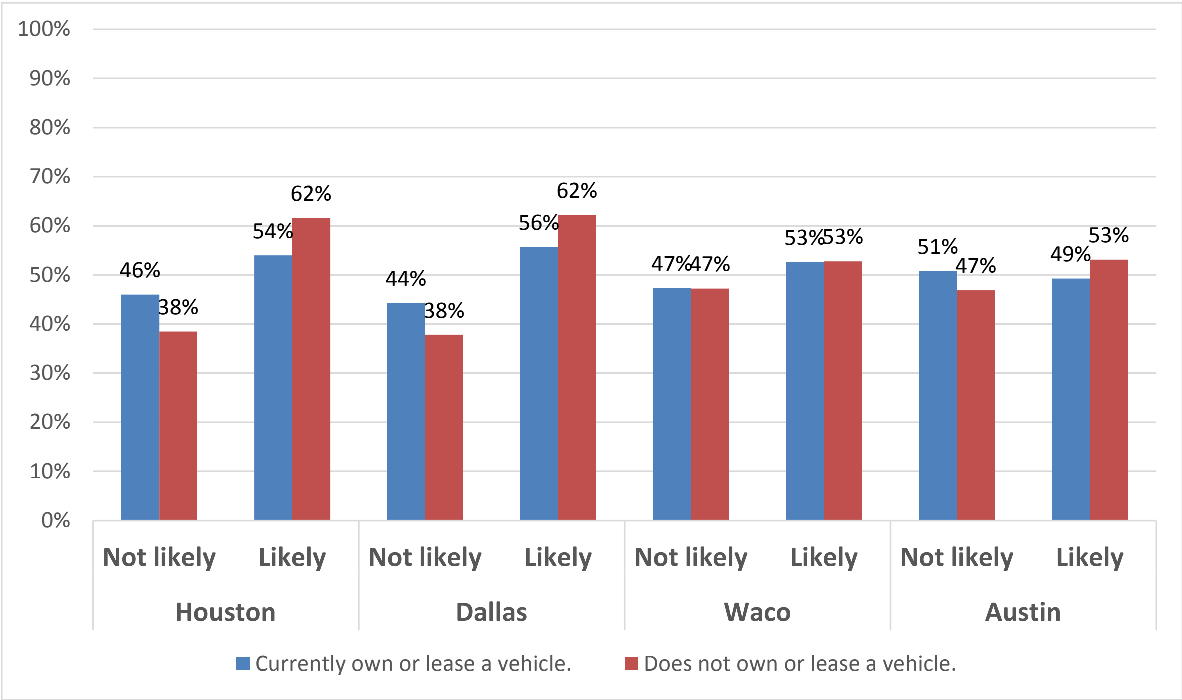


Figure 63. Intent to Use by Vehicle Ownership.

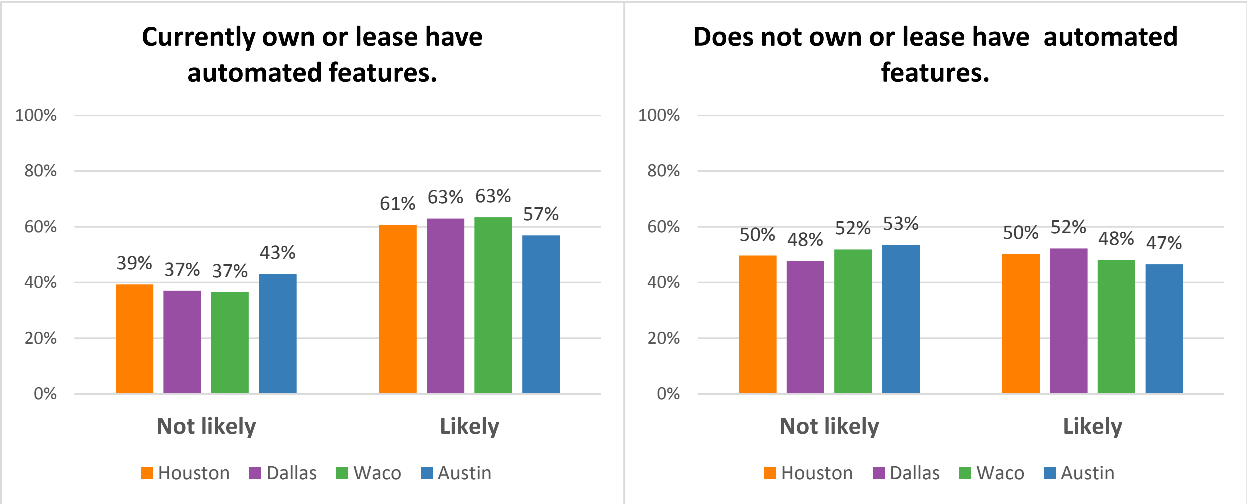


Figure 64. Intent to Use by Vehicle Ownership with Automated Features.

Travel mode. Survey respondents were asked about their commute mode, which was defined as how people usually got to work the previous week (i.e., the single mode used for the longest time). As previously presented in Table 17, more than 85 percent of full- or part-time workers indicated being vehicle drivers in all regions, with the highest percent in Waco (92 percent).

As Figure 65 illustrates, commute mode was related to intent to use. Vehicle drivers were slightly more likely to use self-driving vehicles (ranging from 54 to 57 percent), while this trend was reversed for Austin, with 52 percent of vehicle drivers being unlikely to use. For vehicle passengers, the differences were more distinct and positively skewed toward intending to use, except in Waco, which had an even split. Eighty-nine percent of vehicle passengers reported intent to use self-driving vehicles in Dallas, followed by Austin passengers (77 percent) and then Houston passengers (61 percent).

Though at a lower rate, similar positive trends were also observed for public transit users, except in Waco, which had a considerably lower percentage of individuals who were likely to use self-driving vehicles (33 percent). Keeping in mind very small sample sizes, individuals who walked to commute reported being likely to use self-driving vehicles in all regions except Austin, which had an opposite relationship. The sample size was not adequate to extract a strong conclusion for commute bikers. Finally, telecommuters were less likely to use self-driving vehicles in all regions (around 60 percent) except Dallas, which had a slight majority of respondents more likely to use (52 percent).

Full- and part-time students, who constituted around 15 percent of the overall surveyed sample, were also asked about their school mode. The results were similar to commute mode, with a few exceptions (see Figure 66). Vehicle drivers reported being more likely to use self-driving vehicles in all regions, with Dallas having the highest level at around 68 percent. Vehicle passenger results showed the same positive tendency, except in Waco, which had a significantly lower likelihood of intention to use (20 percent). The results had the same trend as commute mode for public transit passengers with one exception—Austin residents reported a lower likelihood to use self-driving vehicles (39 percent). The same trends were observed for walking to school. Finally, the telecommuter findings were more balanced for school mode compared to commute mode in Houston (48 percent likely to use versus 52 percent not likely to use) and in Waco (45 percent more likely to use versus 55 percent less likely to use). The split was even for Austin telecommuters, and the results suggested more skewness toward intention to use for Dallas telecommuters (67 percent).

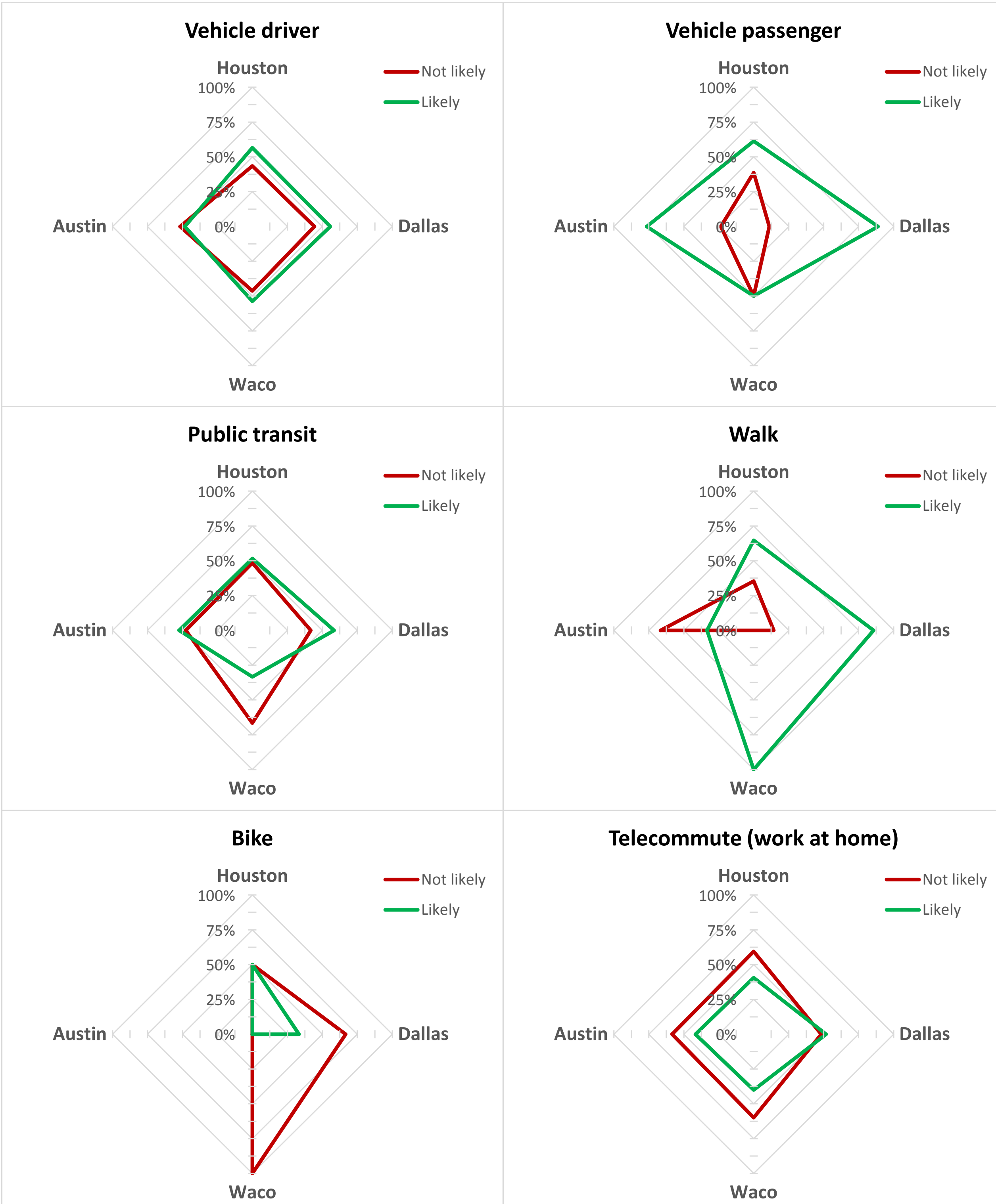


Figure 65. Intent to Use by Commute Mode.

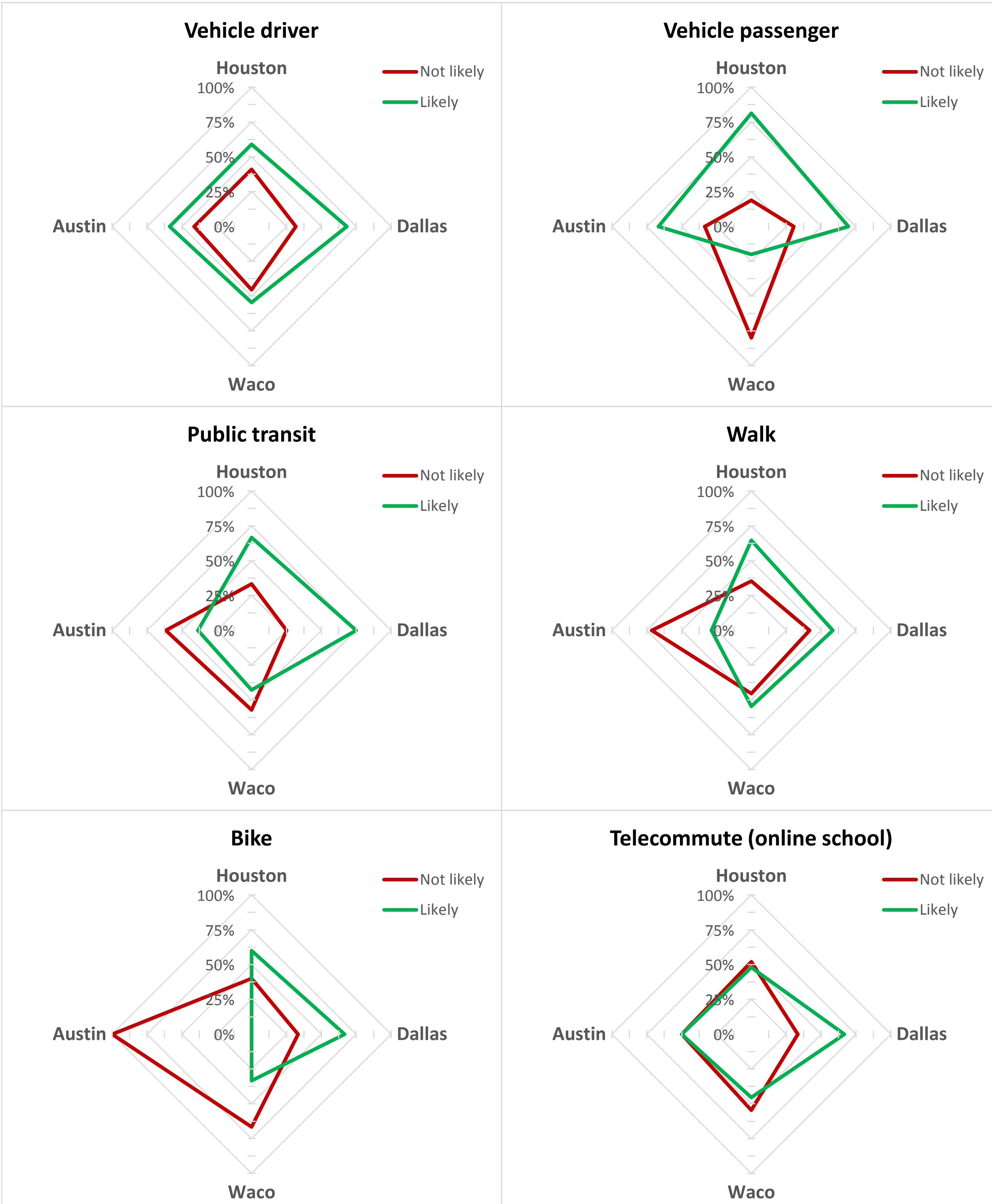


Figure 66. Intent to Use by School Mode.

Driving frequency and miles driven. Figure 67 and Figure 68 present results of the last two travel behavior questions examined: frequency of motor vehicle driving and miles driven during the previous year of the survey, respectively.

Figure 67 suggests a strong intention to use self-driving vehicles across all regions among individuals who almost never drove a car. Austin residents who drove quite infrequently (i.e., a few days a month) still indicated a higher level of intention, which was also the case for Houston and Dallas, though the effect was less significant. The effect was insignificant for infrequent drivers of Waco.

Figure 67. Intent to Use by Frequency of Motor Vehicle Driving.

In terms of self-reported annual VMT, the results did not suggest significant correlation for Austin. Waco also did not provide major associations, except with relatively higher intention to use among individuals who drove more than 15,000 annual miles. In Houston, individuals who had more than 5,000 annual VMT were slightly more likely to use self-driving vehicles. Finally, Dallas had a consistent higher likelihood for using self-driving vehicles, though the respondents who drove between 10,000 and 15,000 annual miles were significantly more likely to use (61 percent) compared to the other VMT categories (see Figure 68).

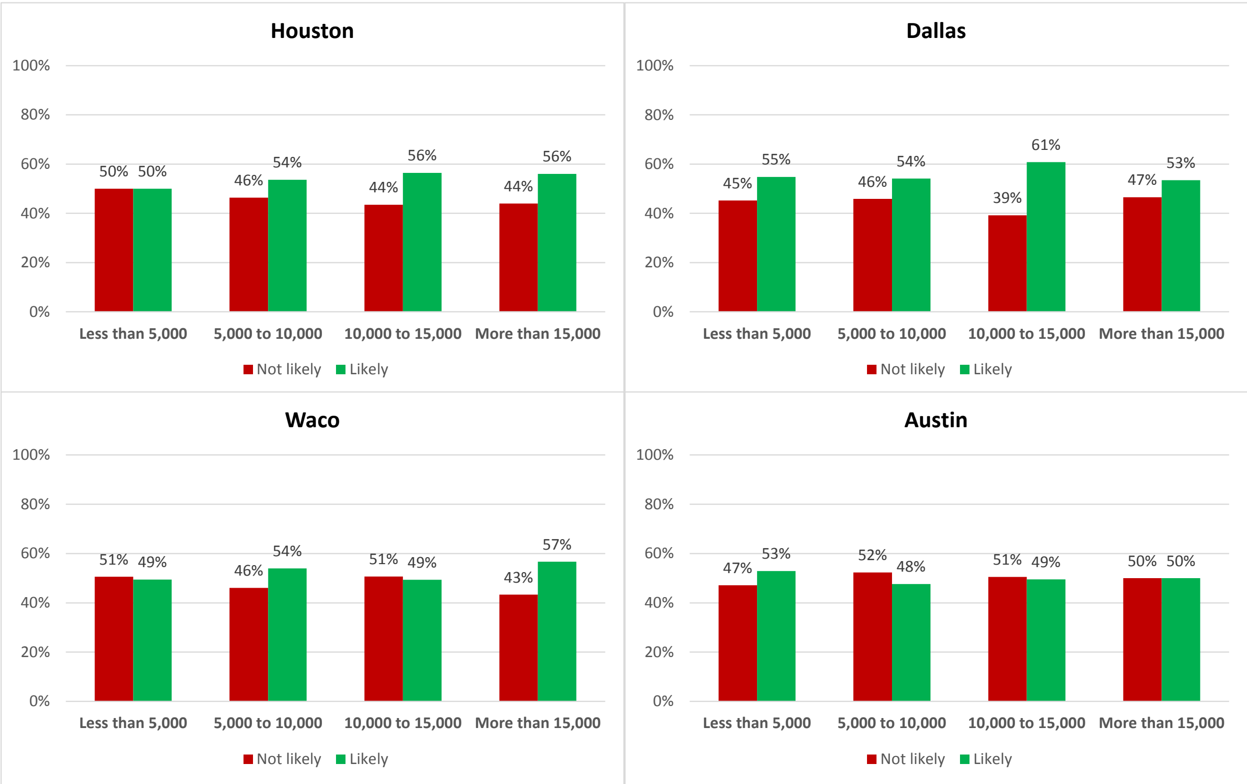


Figure 68. Intent to Use by VMT.

Video Influence on Intent to Use

The final question of the survey asked about the impact of the video on respondents' intent to use. The results were insightful and are presented in Figure 69. Respondents who indicated that video viewing was extremely influential on their intention to use had a highly positive response of intention to use. Reversely, individuals who were not influenced by the video had more negative tendencies toward using self-driving vehicles. Consistently, the results of individuals who reported some influence were accumulated in the central categories. This finding might also indicate that individuals biased toward not being likely to use self-driving vehicles will not be influenced by the video.

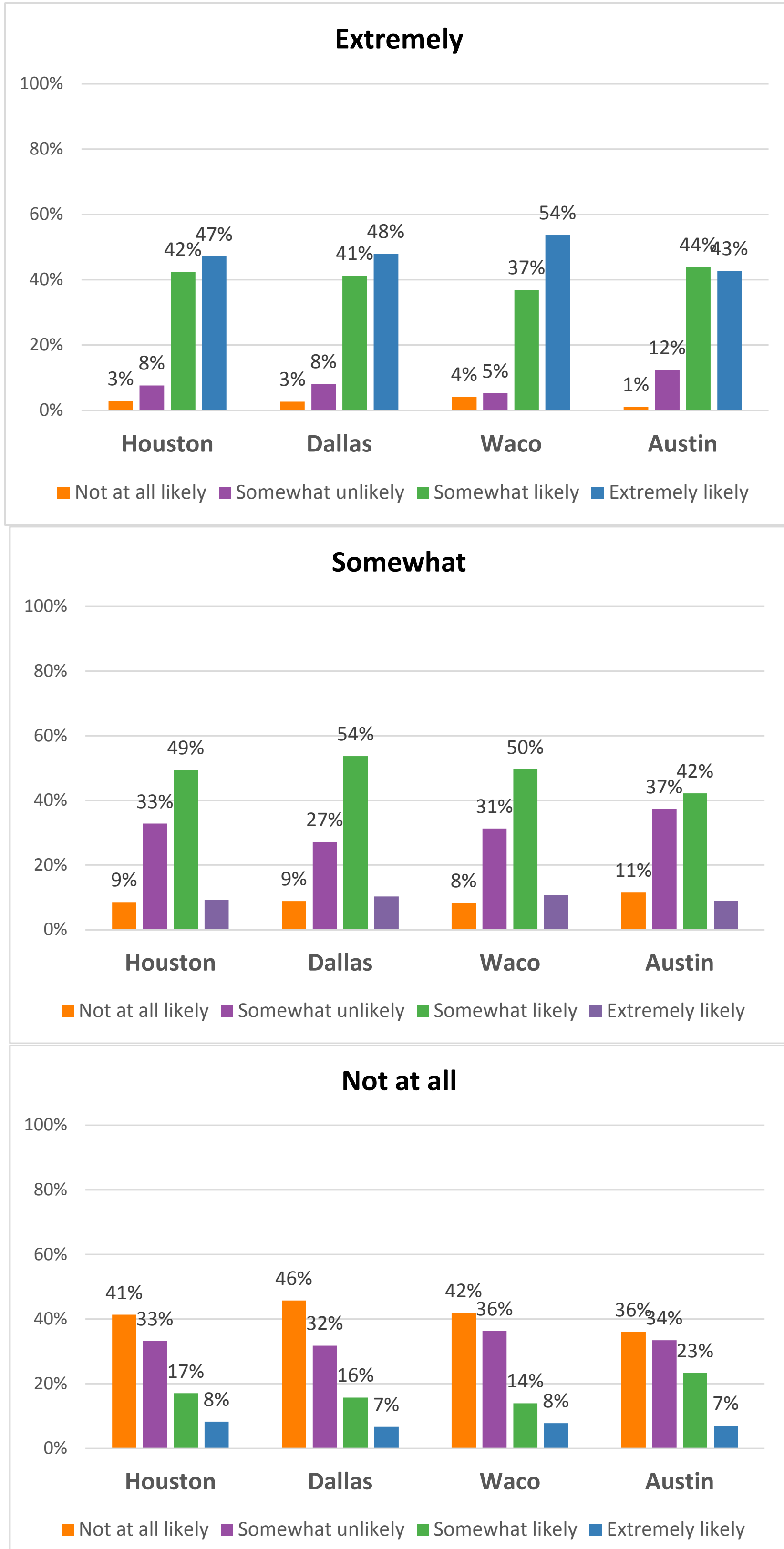


Figure 69. Effect of Self-Driving Vehicle Video on Intent to Use.

Intent to Use by CTAM and Personality Variables

In addition to the individual, household, and travel behavior characteristics, the survey asked several questions aimed to construct psychosocial variables based on the Car Technology Acceptance Model (CTAM), as discussed in Zmud et al. (*75*). The CTAM emphasizes the importance of incorporating psychosocial variables for exploring the adoption and use of new technology and suggests that such psychological or personality-related variables, compared to demographic variables, provide a much stronger role in predicting new technology adoption and use (see *76*, *77*, *78*, and *79* for discussions on technology acceptance models).

Following the underlying theory of the CTAM, respondents were presented with a series of statements regarding their psychological or personality-related characteristics. Then, they were asked to rate their level of agreement with each statement based on a 5-point Likert scale ranging from either *strongly disagree* to *strongly agree* or *very untrue of me* to *very true of me*. These statements were then coded and categorized under different variable domains to form the CTAM and personality variables, as presented in Table 21. The technology use variable (a personality-related variable) was tested with a 5-point frequency scale ranging from *never* to *several times an hour,* as demonstrated in Table 22, indicating strong use of technology across all regions.

Table 21. CTAM and Personality Variables.

CTAM and Personality Variables		Items Compromising
Personality variables	Desire for control	I enjoy making my own decisions.
		I prefer to do something about a problem than to sit by and let it continue.
		I would rather someone else took over leadership role on a group project—*reverse scored.*
		When it comes to orders, I would rather give them than receive them.
	Technology acceptance I	New technology makes people waste too much time—*reverse scored.*
		New technology makes life more complicated—*reverse scored.*
	Technology acceptance II	It is important to keep up with the latest trends in technology.
		Technology will provide solutions to many of our problems.
	Technology use I	Smartphone usage; text messaging; Facebook usage; smartphone transportation apps.
	Technology use II	Other Internet searching; emailing; Internet shopping.
CTAM variables	Performance expectance	If I were to use self-driving vehicles, I would feel safer on driving trips.
	Social influence	People whose opinions I value would like using self-driving vehicles.
	Anxiety about self-driving vehicles	Self-driving vehicles are somewhat frightening to me.
	Effort expectancy	It would be easy for me to become skillful at using self-driving vehicles.
	Attitudes toward self-driving vehicles	Using a self-driving vehicle would be fun.
	Perceived safety	Using a self-driving vehicle would decrease accident risk.

Table 22. Technology Use of Survey Participants.

Technology use	Smartphone usage	Facebook usage	Internet shopping	Other Internet searching	Emailing	Text messaging	Video gaming	Transportation apps
	Houston (N=1532)							
Never	10.4%	21.0%	7.2%	1.7%	1.1%	8.5%	47.7%	32.6%
Several times a month	1.6%	10.6%	45.0%	10.2%	6.6%	8.2%	18.7%	30.0%
Several times a week	5.5%	19.8%	32.8%	24.0%	18.8%	19.2%	16.2%	23.2%
Several times a day	44.5%	38.4%	11.6%	48.0%	49.7%	43.1%	11.7%	10.1%
Several times an hour	38.1%	10.1%	3.5%	16.1%	23.8%	21.0%	5.6%	4.1%
	Dallas (N=1039)							
Never	10.1%	18.9%	6.4%	2.8%	1.3%	6.7%	45.6%	31.9%
Several times a month	2.4%	10.8%	48.3%	9.2%	6.5%	7.9%	20.0%	31.0%
Several times a week	5.4%	19.0%	32.9%	24.4%	18.8%	19.1%	16.7%	24.2%
Several times a day	43.4%	40.4%	7.8%	47.4%	47.9%	43.8%	11.8%	8.7%
Several times an hour	38.7%	11.0%	4.5%	16.2%	25.4%	22.5%	5.8%	4.3%
	Waco (N=526)							
Never	9.7%	18.8%	8.2%	1.5%	1.1%	6.5%	40.7%	34.4%
Several times a month	2.9%	8.6%	49.4%	10.5%	7.2%	9.1%	19.0%	33.3%
Several times a week	4.8%	20.0%	30.8%	23.4%	17.9%	17.3%	19.8%	20.3%
Several times an day	43.3%	41.4%	8.9%	52.1%	54.8%	46.0%	16.2%	8.6%
Several times an hour	39.4%	11.2%	2.7%	12.5%	19.0%	21.1%	4.4%	3.4%
	Austin (N=556)							
Never	9.7%	23.0%	4.7%	1.3%	0.7%	7.2%	55.6%	31.3%
Several times a month	3.1%	9.5%	58.6%	7.9%	4.5%	7.2%	17.3%	32.7%
Several times a week	4.9%	19.6%	27.9%	25.4%	15.1%	19.4%	14.7%	25.7%
Several times a day	41.2%	38.5%	7.2%	52.0%	54.3%	44.8%	8.6%	5.9%
Several times an hour	41.2%	9.4%	1.6%	13.5%	25.4%	21.4%	3.8%	4.3%

To test the strength of association between intent to use and CTAM variables, a bivariate correlation analysis was conducted for each variable. Table 23 presents the results of the correlation analysis, suggesting strong associations between intent to use and all CTAM and personality variables except desire for control. In general, the results indicated similar trends across all regions.

As expected, being anxious about self-driving vehicles was negatively correlated with intention to use, while the remaining variables indicated positive correlation. The largest associations with intent to use were observed for performance expectance, social influence, attitudes toward self-driving vehicles, and perceived safety. Performance expectance (i.e., "If I were to use self-driving vehicles, I would feel safer on driving trips") was the CTAM variable with the highest effect size representing the largest association for Houston, Dallas, and Austin, whereas attitudes toward self-driving vehicles (i.e., "Using a self-driving vehicle would be fun") had the highest effect size for Waco.

Table 23. Correlation Analysis for CTAM and Personality Variables.

CTAM and Personality Variables		**Spearman's Correlation Coefficient**			
		Houston	**Dallas**	**Waco**	**Austin**
		N=1532	N=1039	N=526	N=556
Personality variables	Desire for control*	0.034*	0.017*	0.045*	0.080*
	Technology acceptance I	0.192	0.137	0.223	0.163
	Technology acceptance II	0.321	0.329	0.305	0.223
	Technology use I	0.209	0.208	0.208	0.142
	Technology use II	0.201	0.209	0.241	0.157
CTAM variables	Performance expectance	0.663	0.672	0.649	0.736
	Social influence	0.591	0.607	0.588	0.590
	Anxiety about self-driving vehicles	−0.456	−0.447	−0.458	−0.437
	Effort expectancy	0.433	0.440	0.438	0.348
	Attitudes toward self-driving vehicles	0.644	0.654	0.656	0.639
	Perceived safety	0.594	0.602	0.607	0.662

* All correlations were significant at the 0.01 level except "desire for control."

Finally, Figure 70 through Figure 91 present the radar charts of intent to use by each CTAM and personality variable, supporting the correlation analysis and revealing the strong associations between intent to use and the CTAM variables.

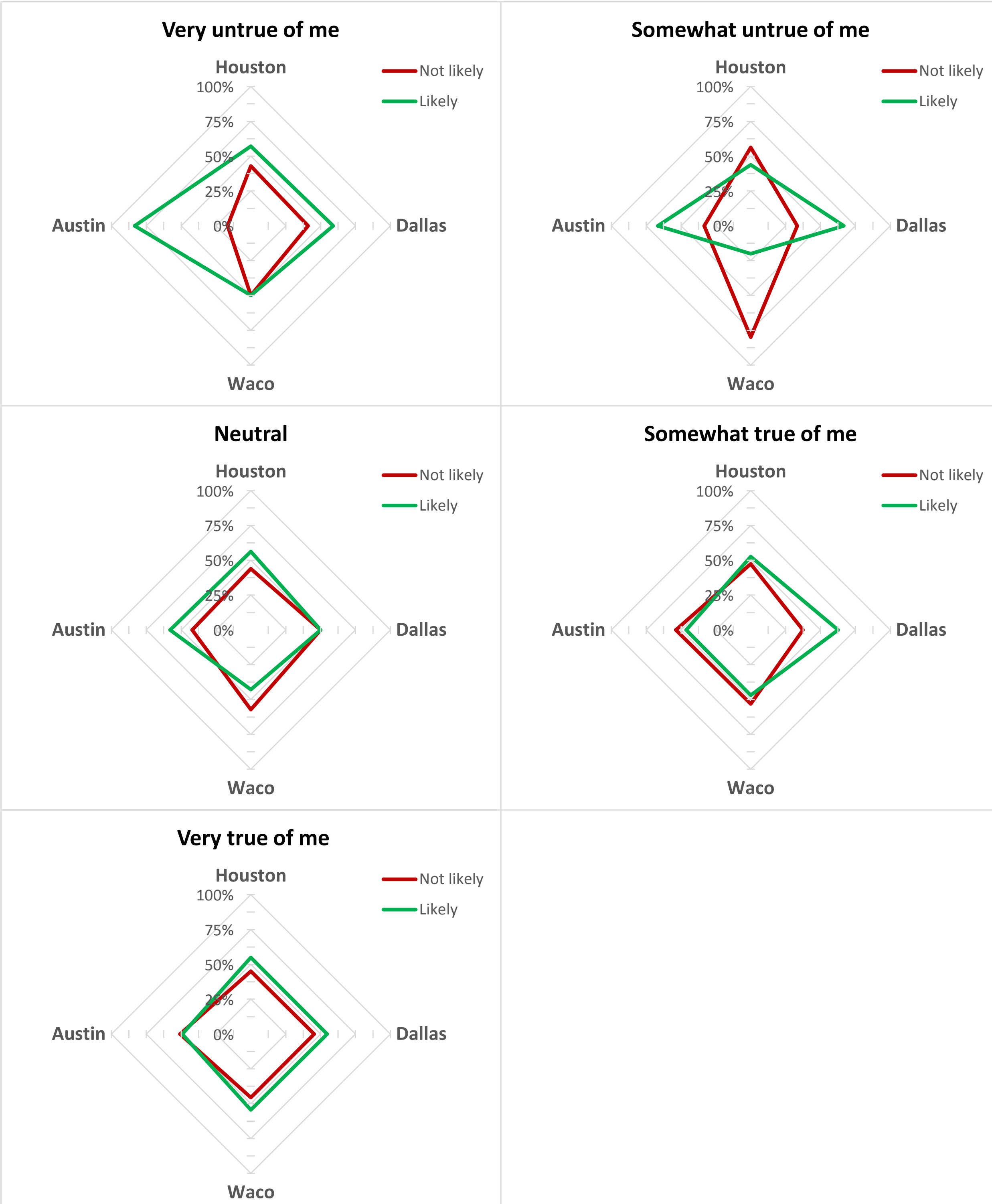


Figure 70. Intent to Use by Desire for Control A: "I Enjoy Making My Own Decisions."

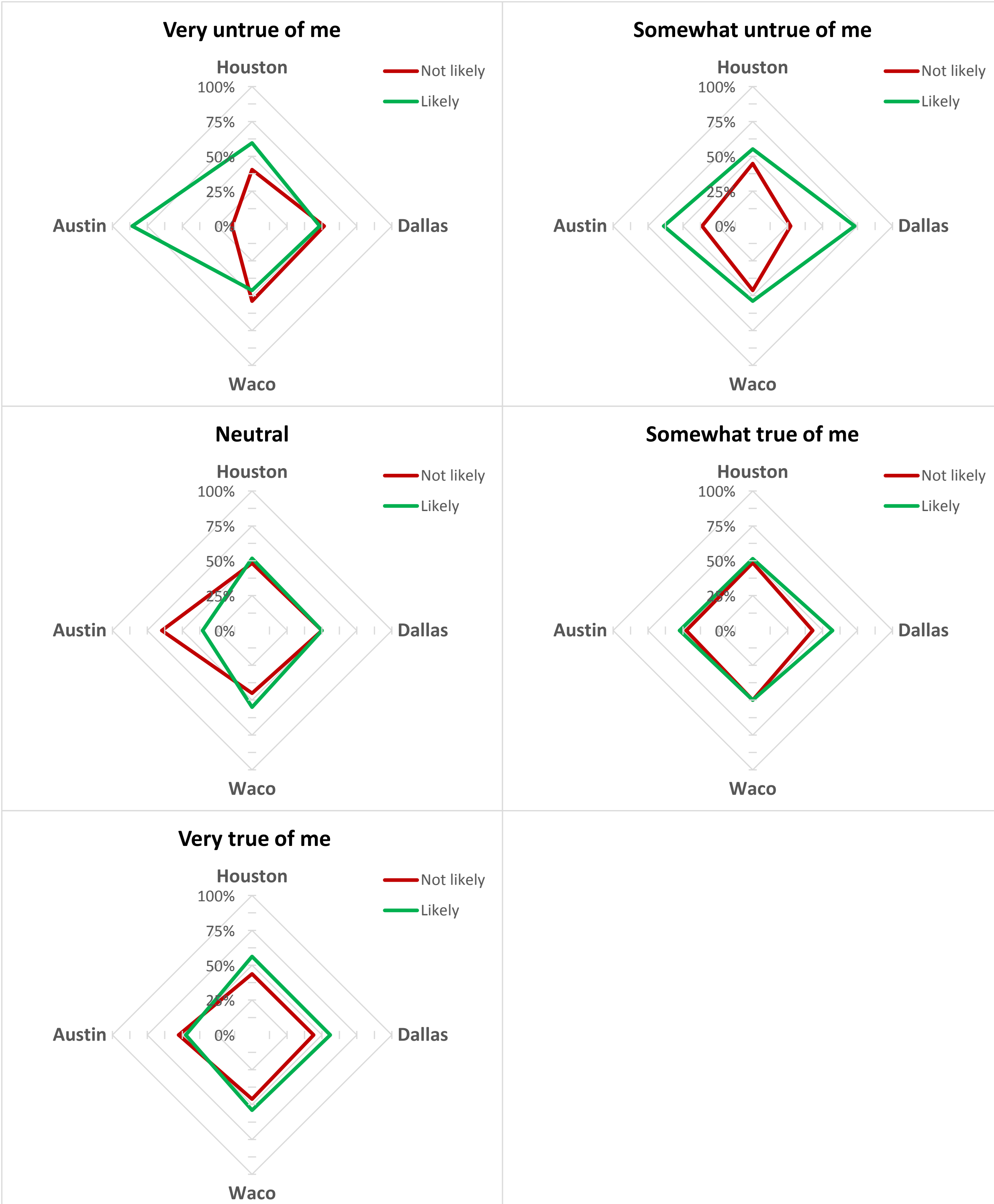


Figure 71. Intent to Use by Desire for Control B: "I Prefer to Do Something about a Problem Than to Sit By and Let It Continue."

Figure 72. Intent to Use by Desire for Control C: "I Would Rather Someone Else Took over Leadership Role on a Group Project"—Reverse Scored.

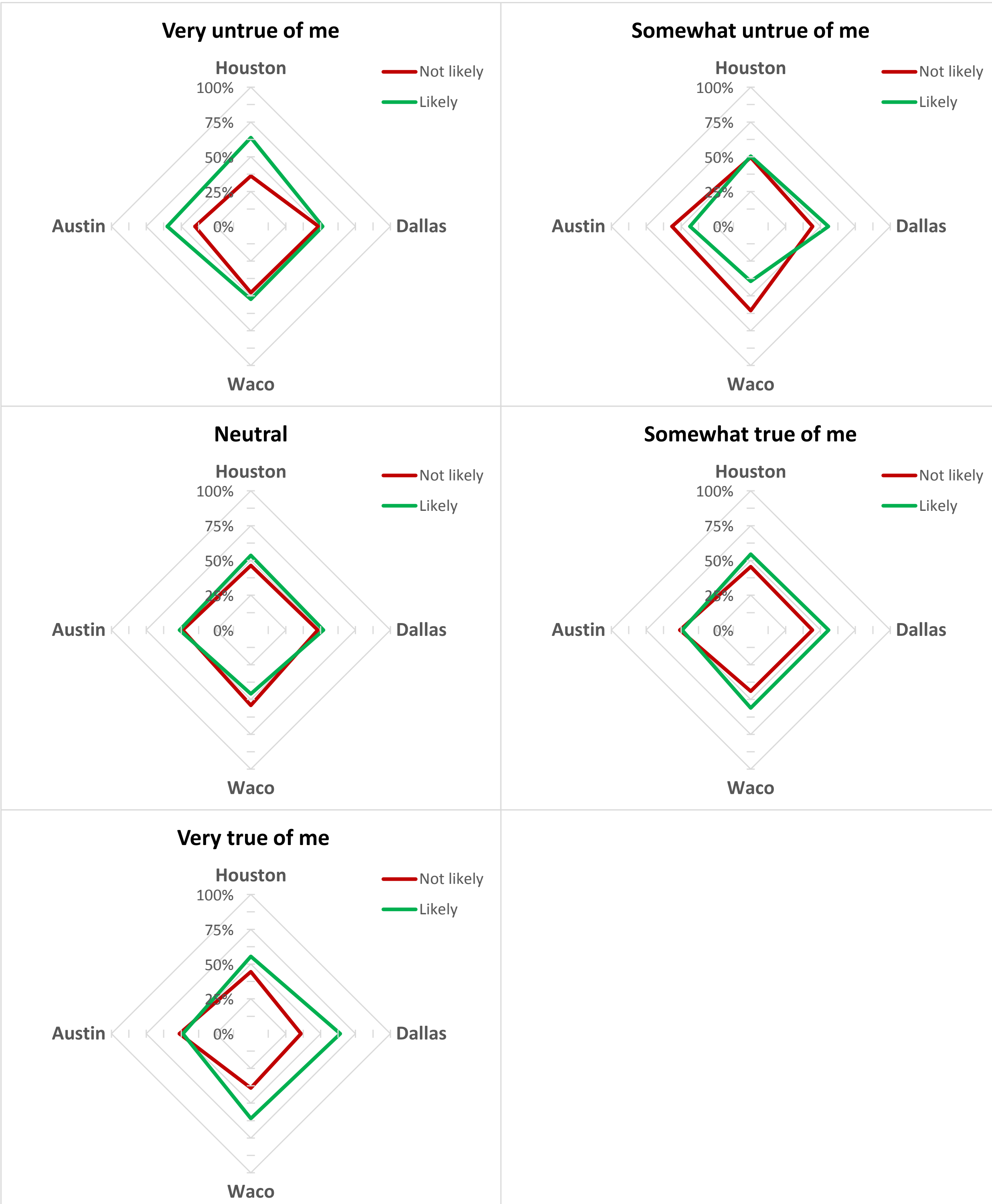


Figure 73. Intent to Use by Desire for Control D: "When It Comes to Orders, I Would Rather Give Them Than Receive Them."

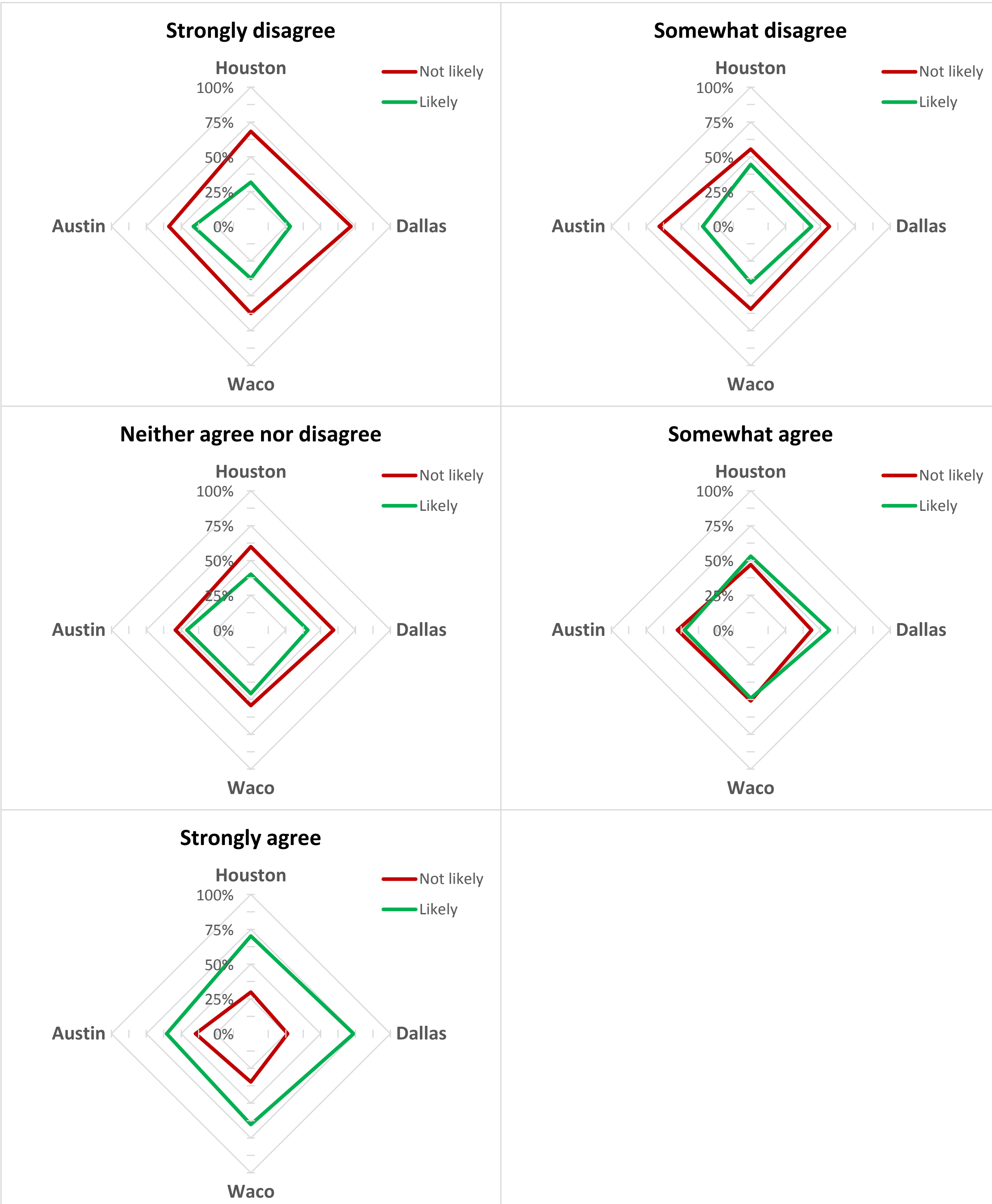


Figure 74. Intent to Use by Technology Acceptance A: "It Is Important to Keep Up with the Latest Trends in Technology."

Figure 75. Intent to Use by Technology Acceptance B: "New Technology Makes People Waste Too Much Time"—Reverse Scored.

Figure 76. Intent to Use by Technology Acceptance C: "New Technology Makes Life More Complicated"—Reverse Scored.

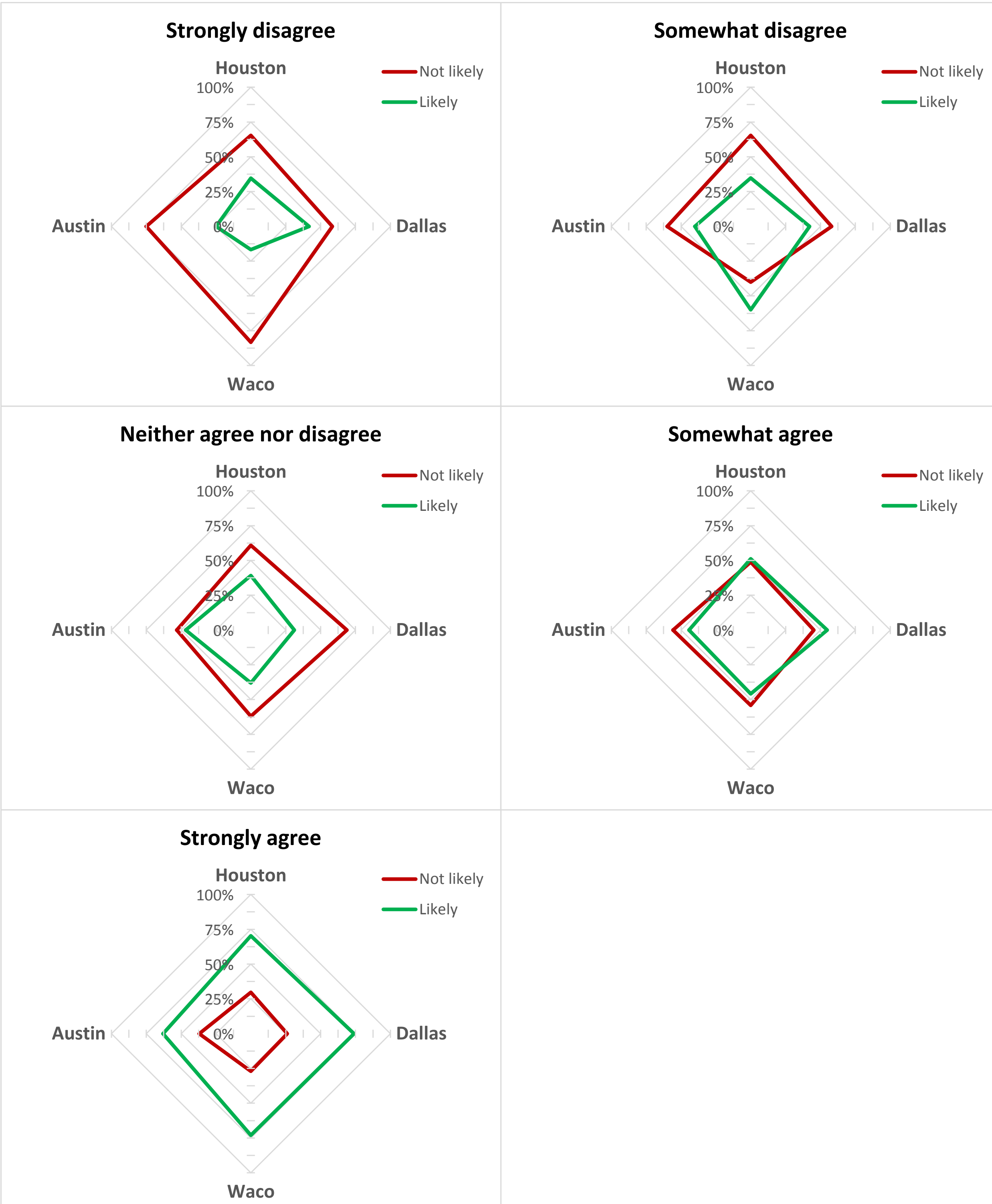


Figure 77. Intent to Use by Technology Acceptance D: “Technology Will Provide Solutions to Many of Our Problems.”

Figure 78. Intent to Use by Technology Use A: "Smartphone Usage."

Figure 79. Intent to Use by Technology Use B: "Facebook Usage."

Figure 80. Intent to Use by Technology Use C: "Internet Shopping."

Figure 81. Intent to Use by Technology Use D: “Other Internet Searching.”

Figure 82. Intent to Use by Technology Use E: "Emailing."

Figure 83. Intent to Use by Technology Use F: "Text Messaging."

Figure 84. Intent to Use by Technology Use G: "Video Gaming."

Figure 85. Intent to Use by Technology Use H: "Smartphone Transportation Apps."

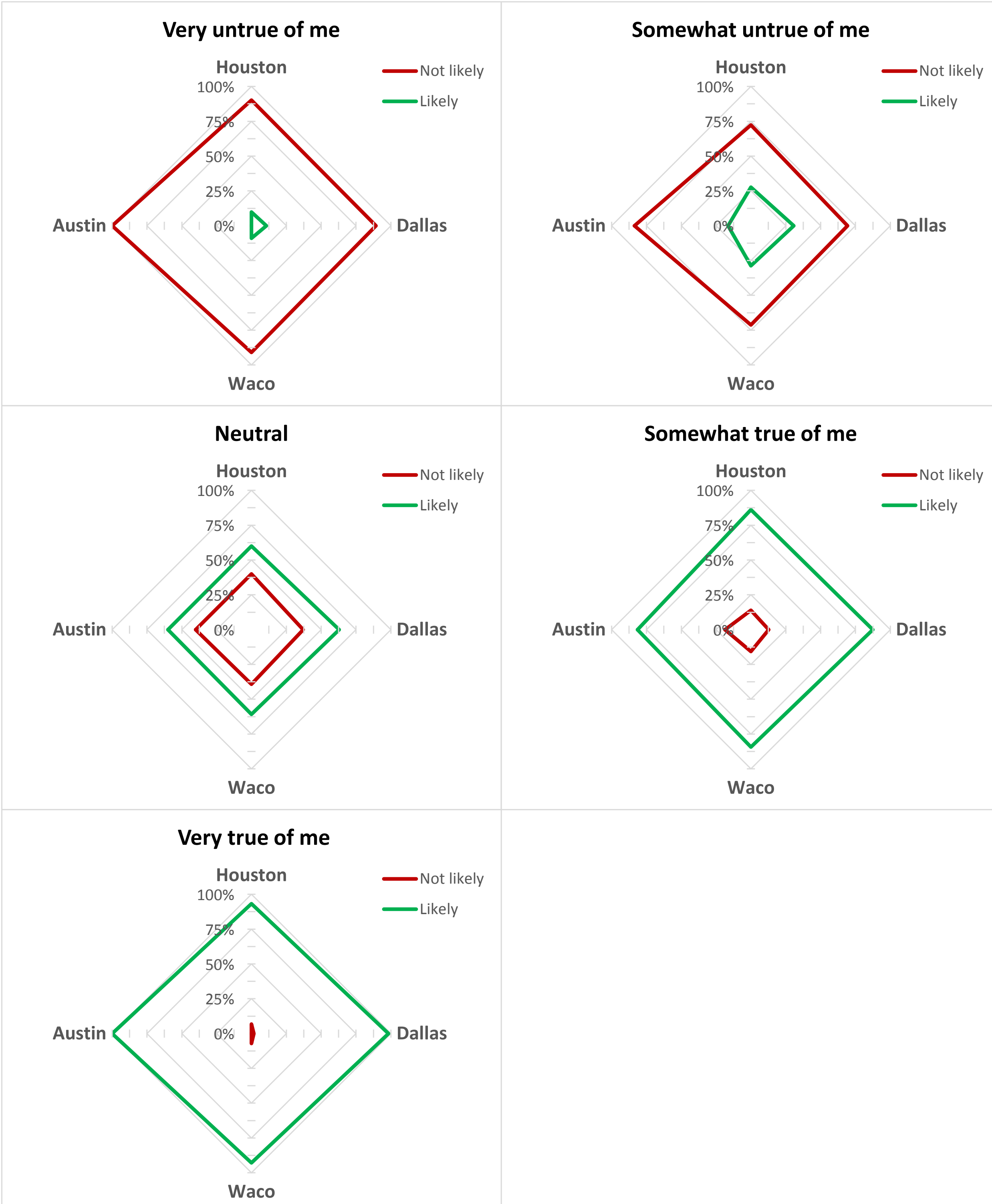


Figure 86. Intent to Use by Performance Acceptance: "If I Were to Use Self-Driving Vehicles, I Would Feel Safer on Driving Trips."

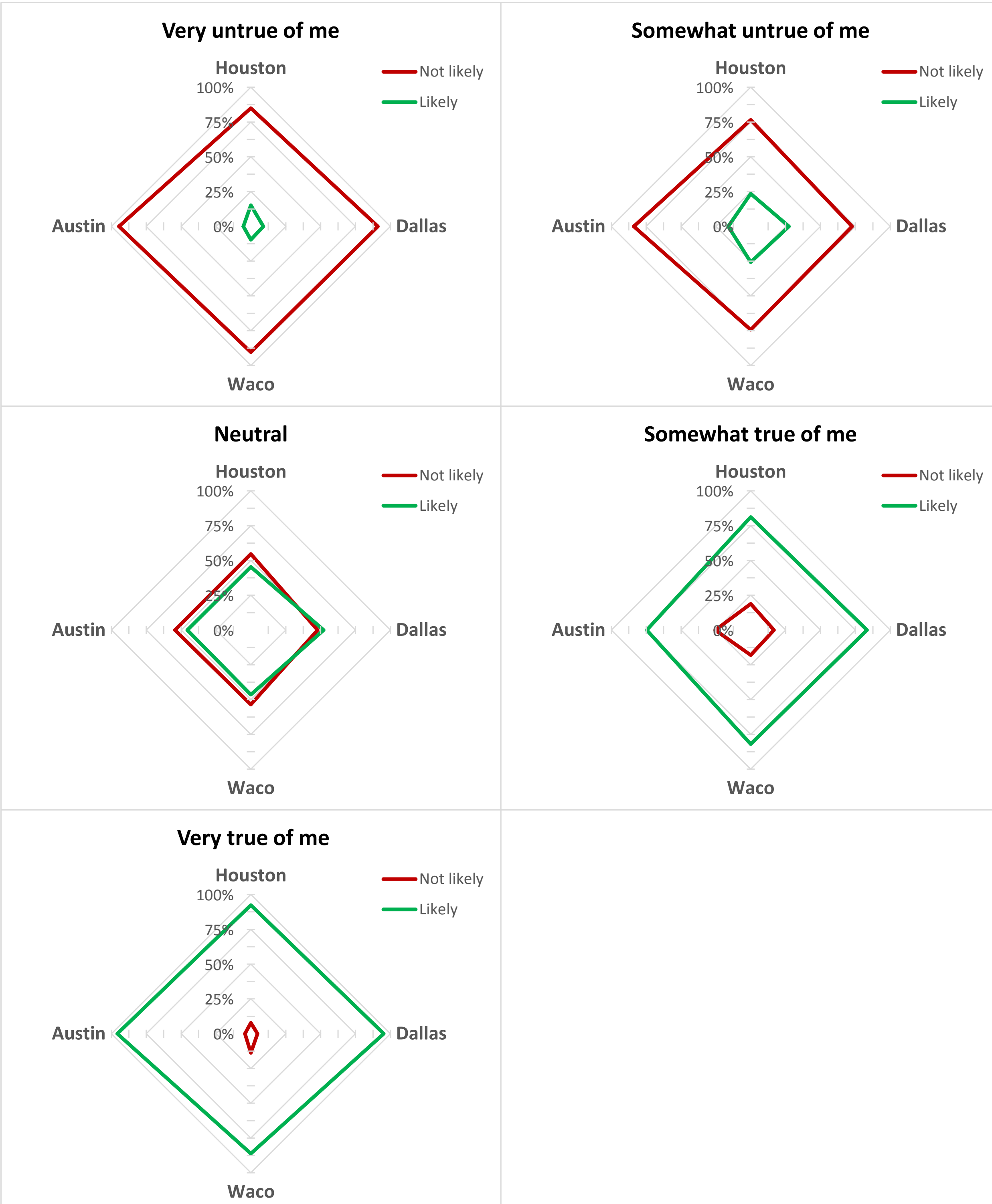


Figure 87. Intent to Use by Social Influence: "People Whose Opinions I Value Would Like Using Self-Driving Vehicles."

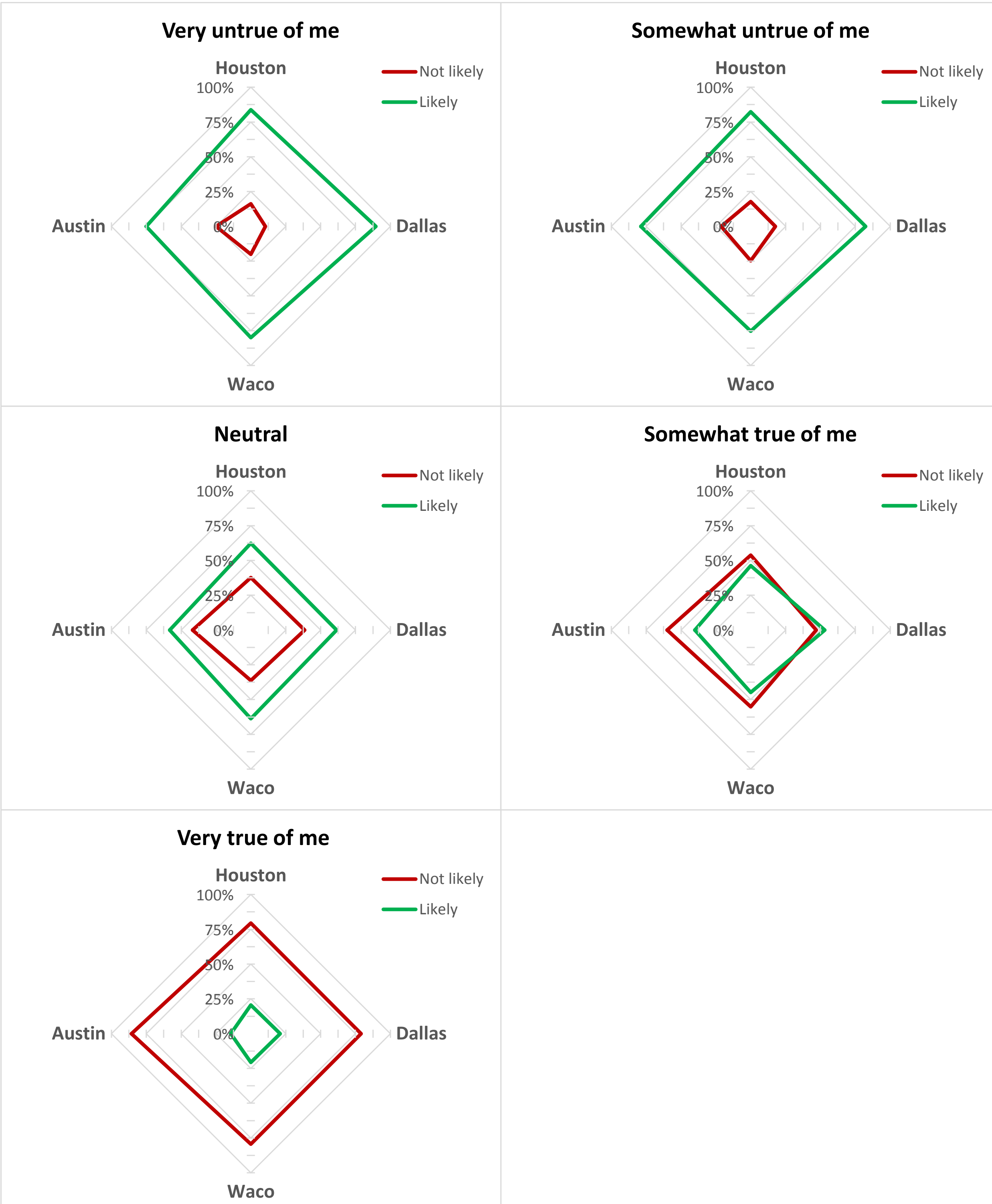


Figure 88. Intent to Use by Anxiety about Self-Driving Vehicles: "Self-Driving Vehicles Are Somewhat Frightening To Me."

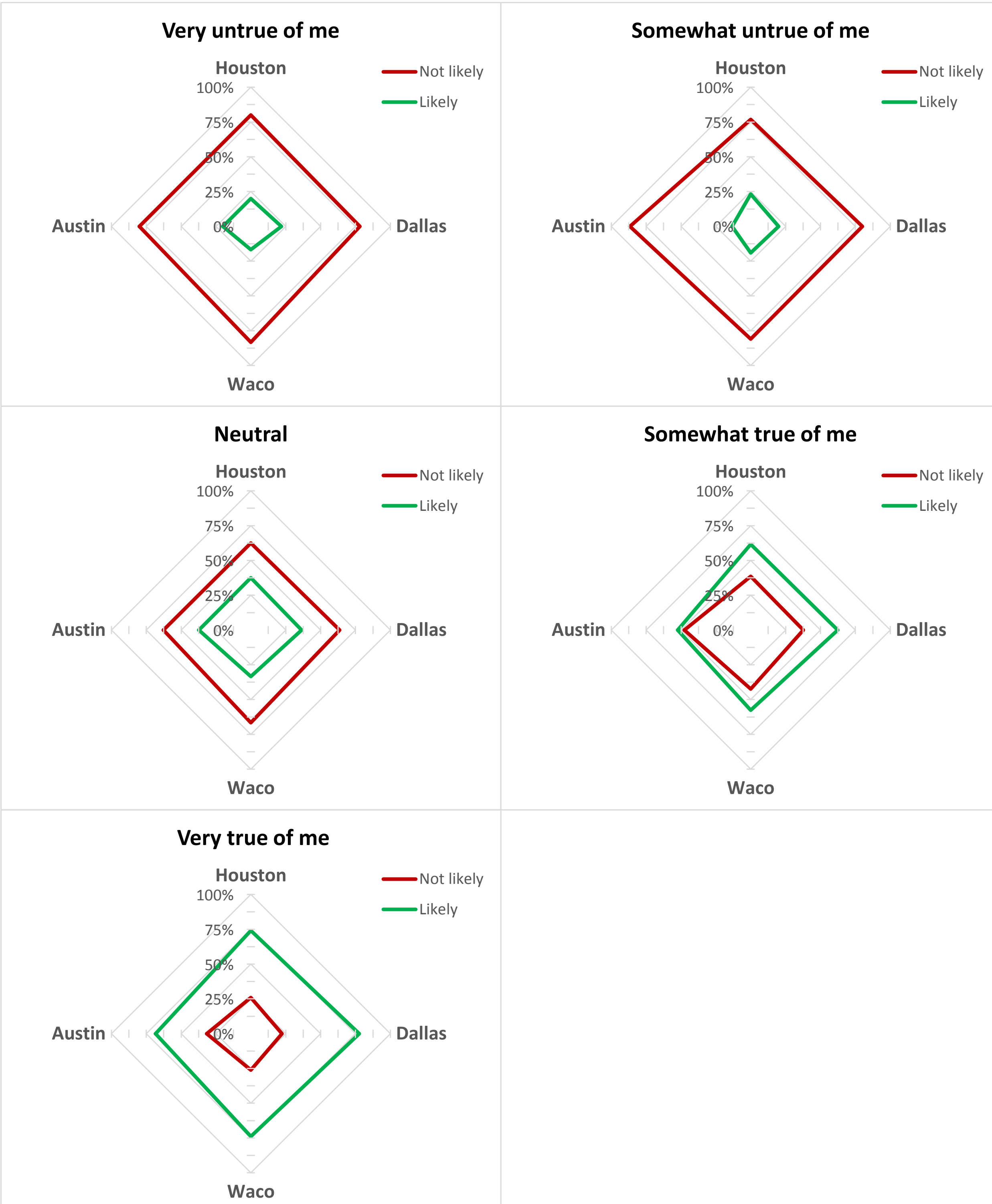


Figure 89. Intent to Use by Effort Expectancy: "It Would Be Easy for Me to Become Skillful at Using Self-Driving Vehicles."

Figure 90. Intent to Use by Attitudes toward Self-Driving Vehicles: "Using a Self-Driving Vehicle Would Be Fun."

Figure 91. Intent to Use by Perceived Safety: "Using a Self-Driving Vehicle Would Decrease Accident Risk."

CHAPTER 7. 2016 TEXAS AV/CV STAKEHOLDER WORKSHOPS

INTRODUCTION

In May and June of 2016, the project research team conducted three automated/connected vehicle stakeholder planning workshops as part of Task 6. The objective of the workshops was to engage regional TxDOT, MPO, and other transportation professionals to consider AV/CV technology impacts in the transportation planning process.

One workshop was planned for each of three locations in Texas: Arlington, Austin, and Houston. Invitees consisted mainly of planners from MPOs, staff from area TxDOT districts, and any students or consultants that planners or TxDOT staff invited. Because the Houston workshop was held in conjunction with the annual Transportation Planning Conference, staff from TxDOT's Transportation Planning and Programming Division also attended.

PARTICIPANT INFORMATION

Figure 92 displays the participant information according to breakdown by type of employer.

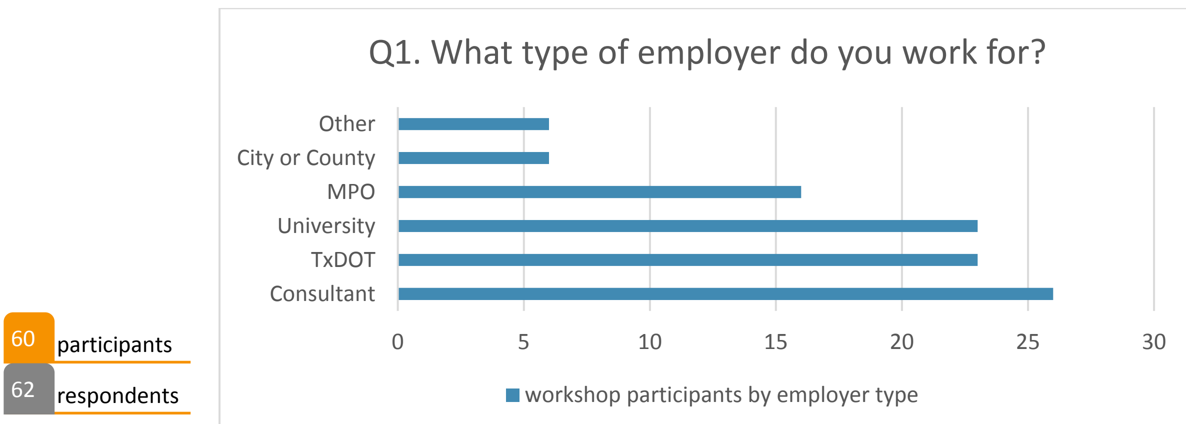


Figure 92. Workshop Participants by Employer Type.

WORKSHOPS

The workshops lasted four hours and began with introductory, high-level remarks from researchers about the current state of AV/CV development and deployment. A discussion in four parts followed, structured by presentations of four different scenarios:

- The RoboTaxi Utopia: A Mobility Nirvana?
- Deliver Me from Inefficiency: Automated Freight, Goods and Service Delivery.
- Bus Me Up, Scotty: Automation Impacts to Public Transportation.
- Design Your Own Future: Scenario Planning and Automation.

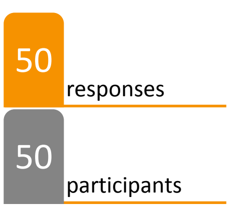
Researchers first presented a PowerPoint on each of the above topics and then posed questions about the topic in an electronic, real-time polling format called PollEV. Participants logged in to a website by computer or cell phone, joined the project's active poll, and responded to questions in real time. Polling results were projected on a large screen at the head of the room so that everyone was able to see the results immediately. This exercise was designed to generate discussion on each topic.

Following are the poll results and discussion summaries of each topic, all presented in aggregate form representing all three workshop discussions.

Topic 1: The RoboTaxi Utopia: A Mobility Nirvana?

This presentation asked participants to imagine passenger travel in a future where the sharing economy prevails and people share automated and mostly electric vehicles, resulting in fewer privately owned vehicles per person on the road than is seen today. In this scenario, dynamic ridesharing is also common so that people only call for cars when they need them and often share those rides with others, just as one would with traditional carpooling. Depending on how autonomous or connected those vehicles are, speed and route harmonization across a region might be possible. Shared autonomous vehicles might change the need for long-term parking and could decrease congestion.

For Topic 1, participants were asked three questions related to the RoboTaxi scenario. The first had to do with the biggest benefit of the scenario. Figure 93 displays the results.



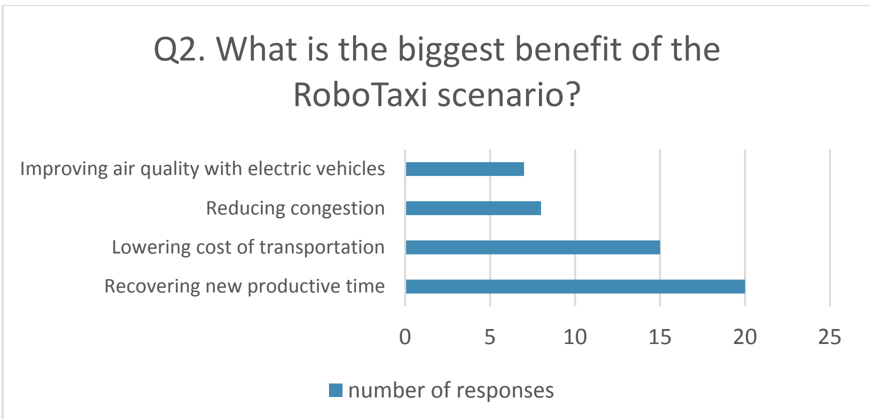


Figure 93. Biggest Benefit of RoboTaxi Scenario.

After the results related to the benefits were revealed, participants discussed the scenario, as summarized below.

> Congestion could increase or decrease, depending on whether or not people shared vehicles. Sharing vehicles might also reduce the need for vehicle ownership entirely, and

the risk of carrying insurance would certainly shift in some way, possibly away from the driver.

Current road design is built to accommodate rule-breaking drivers. Assuming AVs will follow the rules, road design could change.

With increased efficiency, throughput might increase even if volume goes up.

The data processing required for this scenario to work will require large and secure servers. Is the current bandwidth dedicated to it (DSRC) big enough to accommodate future demand? And who will own the data? It will be crucial to monitor, understand, and respond to the changes in travel patterns. If services or vehicles are privately owned, will companies share with the government?

Next, participants were asked about major issues with the RoboTaxi scenario. Figure 94 illustrates the results.

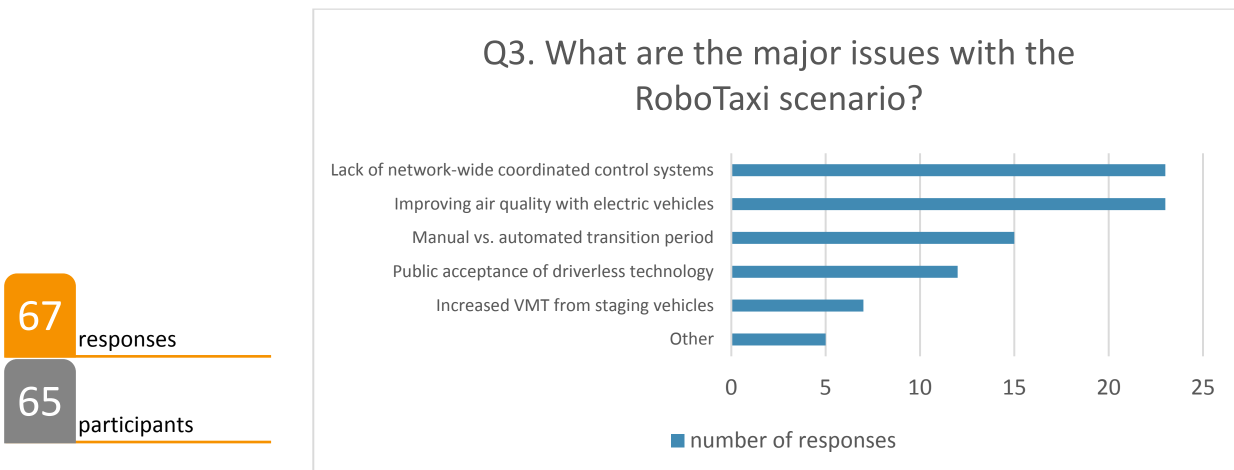


Figure 94. Major Issues with the RoboTaxi Scenario.

Once the results were revealed, the following discussion ensued.

Not having a coordinated control system leaves many questions unanswered: Who will own the data? What, or who, will be operating the system that makes the decisions? Will we have new, centralized traffic management centers? Will we trust government or agencies to control our routes?

The assumption about price right now is that AVs will be expensive. How will that affect market penetration? And what about equity? If it is affordable for many, will that disincentivize sharing rides and using transit? Will cars be the same shape and size? Is this an opportunity to create smaller, more-efficient vehicle choices?

Are there threatened industries or transportation-related labor unions trying to block development of elements of this scenario?

Finally, participants were asked to rank the risks of the RoboTaxi scenario. Figure 95 displays the results.

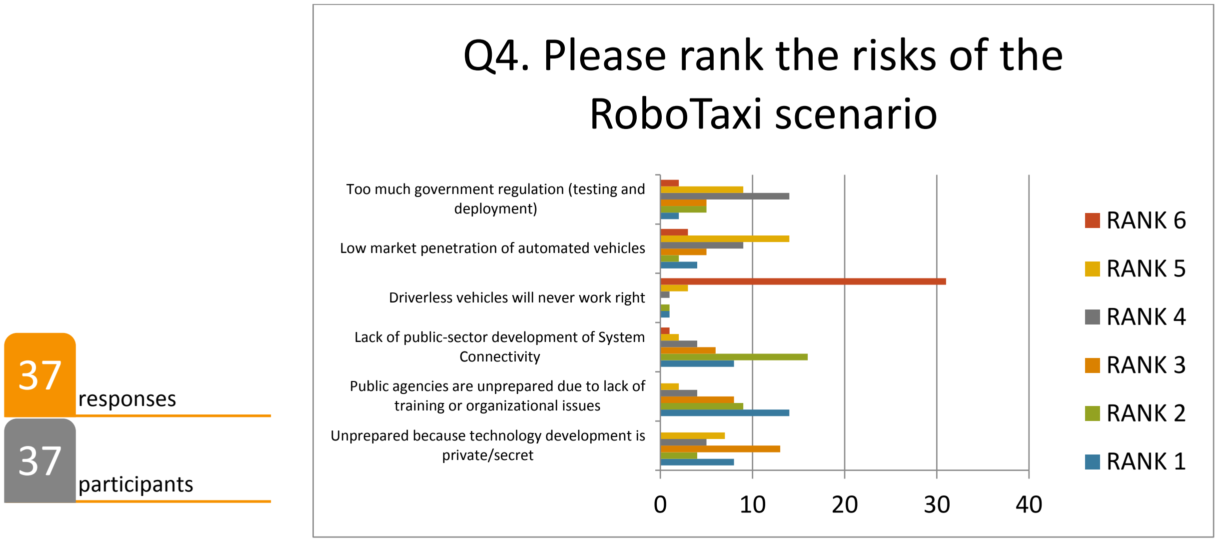


Figure 95. Risks of the RoboTaxi Scenario.

Participants then discussed the rankings, as follows.

Since so much of this technology is being developed privately, without some regulation or cooperation, we may not all be using the same robust systems and may not get the optimization of this scenario. If signal controls can't even talk to each other now, how can we expect that all these other systems will be able to do that? And how much control are we willing to give over to private companies of our private data?

And how will we protect against a power failure if there is not solid public-sector involvement?

Topic 2: Deliver Me from Inefficiency: Automated Freight, Goods, and Service Delivery

In this scenario, several freight sectors were affected by automation. Participants considered truck platooning, electric containerized shipping on fixed guideways (freight shuttle), ice chest robots, and box drones. Truck platooning could reduce drag and headway, save fuel and labor costs, and mitigate the driver shortage. If truck platooning replaced drivers for long-haul routes, drivers could drive short-haul routes and sleep in their own beds at night.

Participants were asked two questions related to the scenario. The first focused on the major challenge of automated package delivery. Figure 96 is a compilation of the results.

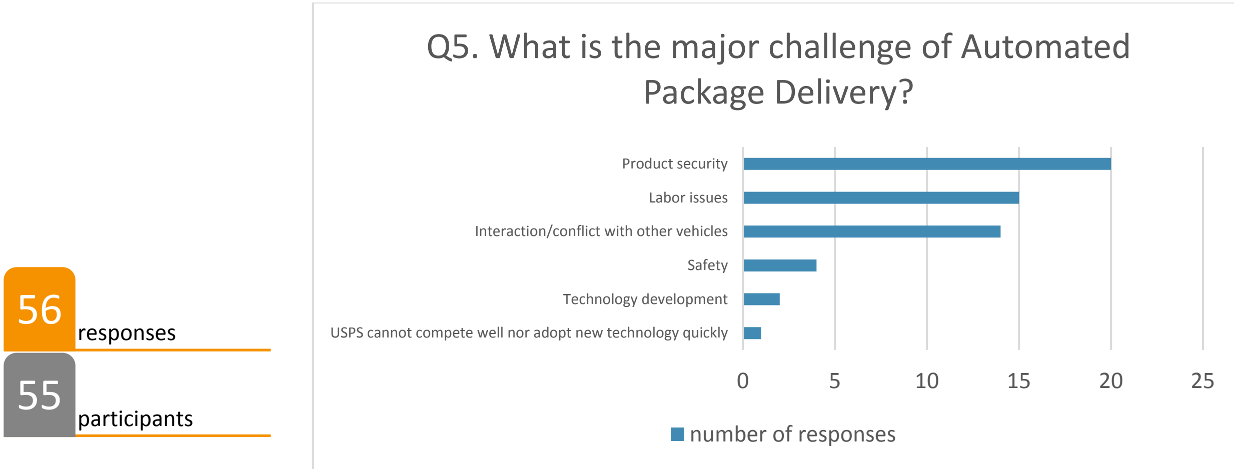


Figure 96. Major Challenge of Automated Package Delivery.

Following is a summary of the related discussion.

> When asked about increased home delivery service now compared to 10 years ago, most participants affirmed an increase. Does this create a heightened sense of vulnerability? Drones are considered unmanned aircraft. Will there be a weight limit on what they can deliver? Do box drones pose a new, airborne risk?
>
> Labor will certainly be an issue, and the rail sector may resist.

Next, participants were asked to rank the benefits of truck platooning, as shown in Figure 97.

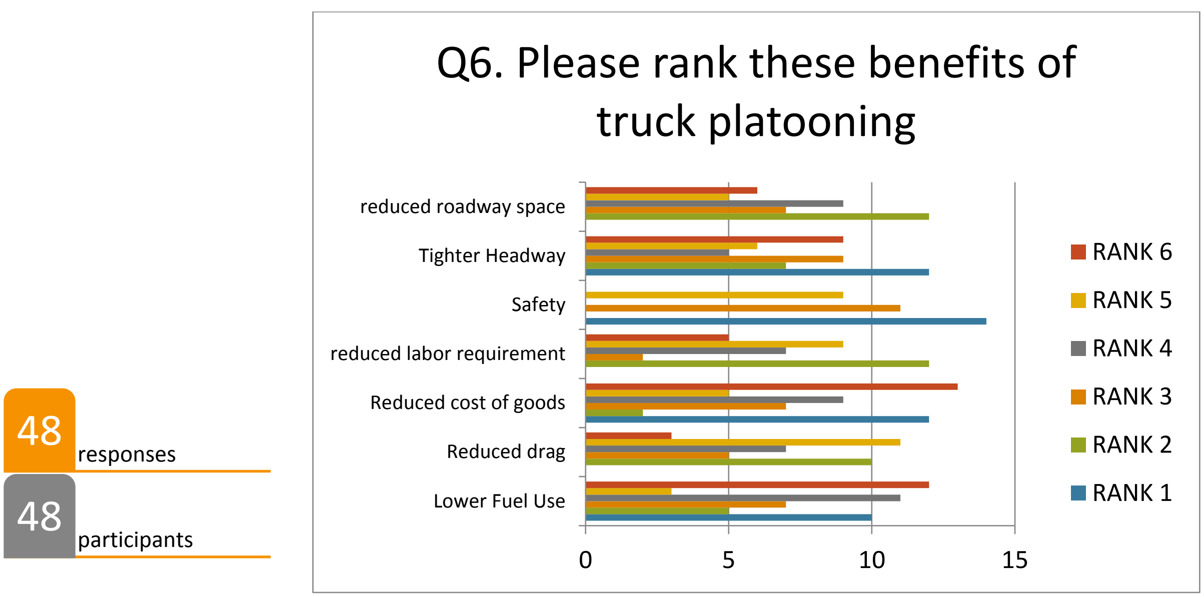


Figure 97. Benefits of Truck Platooning.

Following is a summary of the discussion based on the rankings.

> Many changes need to take place besides technology development for this to be effective. Off-peak deliveries may not change much since scheduling is determined by so much more than congestion.
>
> What about the job of driver? Will platoon drivers be a new, high-skilled labor position? Will there be two kinds of drivers: one for long hauls and one for backing up and loading? That is a really specific skill set. Will the trucking industry be the early implementers since they are suffering a driver shortage? And if they could sleep in the truck while it's driving, drivers wouldn't necessarily have to limit their shifts to eight hours.
>
> If lower fuel use and cost are really a possible benefit, wouldn't we have seen the trucking industry embrace platooning by now?
>
> Big trucks at high speeds on highways are easier to address than smaller vehicles at lower or changing speeds on city streets. Will there be a cap on truck speeds in platoons?
>
> Will truck platooning make other containerized technologies, like the freight shuttle, obsolete? The freight shuttle might work better in areas like ports and border crossings than for long-haul trips.

Topic 3: Bus Me Up, Scotty: Automation Impacts on Public Transportation

The guiding question of the presentation on Topic 3 was whether AV/CVs will replace, enhance, or transform existing transit service. There has been some discussion that TNCs are replacing transit, but some data suggest that TNCs may be serving transit, especially where first- and last-mile connections are an issue. It seems unlikely that in dense urban areas, people can be taken out of mass transit vehicles to get them all downtown at the same time. There is not enough capacity to accommodate that many new vehicles, so without mass transit, automation probably will not reduce congestion.

Vehicle design will be important for an automated transit system. Why should it always be a bus? Could it be separate containers, like pods? There is a design for a high-speed bus in Tucson; why not design something that can use existing infrastructure?

For this topic, respondents were asked two polling questions. The first question focused on the biggest change that AV/CVs could have on transit. Figure 98 summarizes the results.

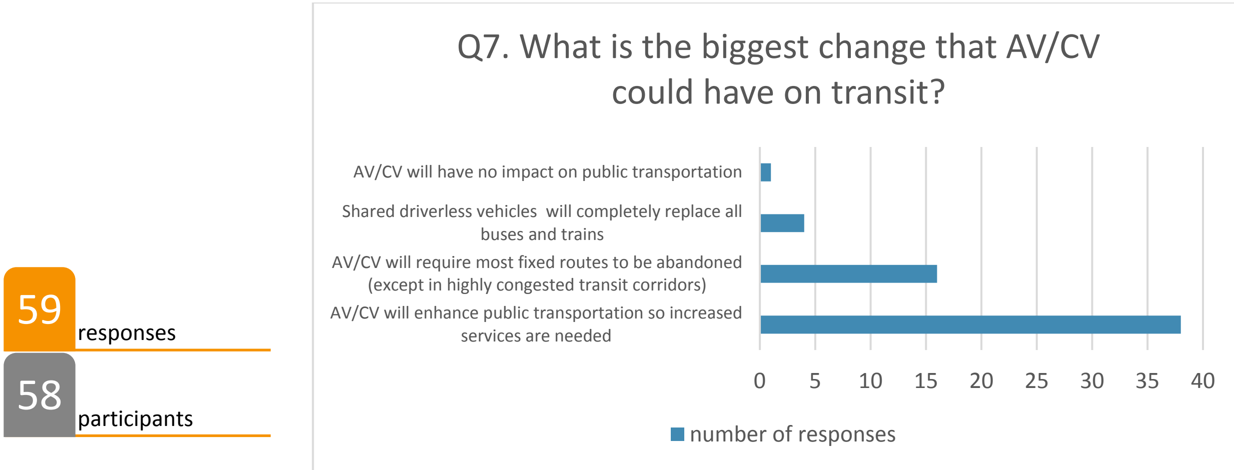


Figure 98. The Biggest Change AV/CVs Could Have on Transit.

A summary of the discussion on transit-related changes follows.

> Some transit agencies are trying to figure out how not to be obsolete and are considering how to partner with TNCs to solve first/last-mile issues, maybe by offering incentives for travelers to use both services if doing so results in a complete journey with no gaps. One effect of TNCs is that the more people use them, the more they get used to riding with other people and in other people's vehicles.

Participants were next asked whether major investments in public transportation should be put on hold because of AV/CV development (see Figure 99).

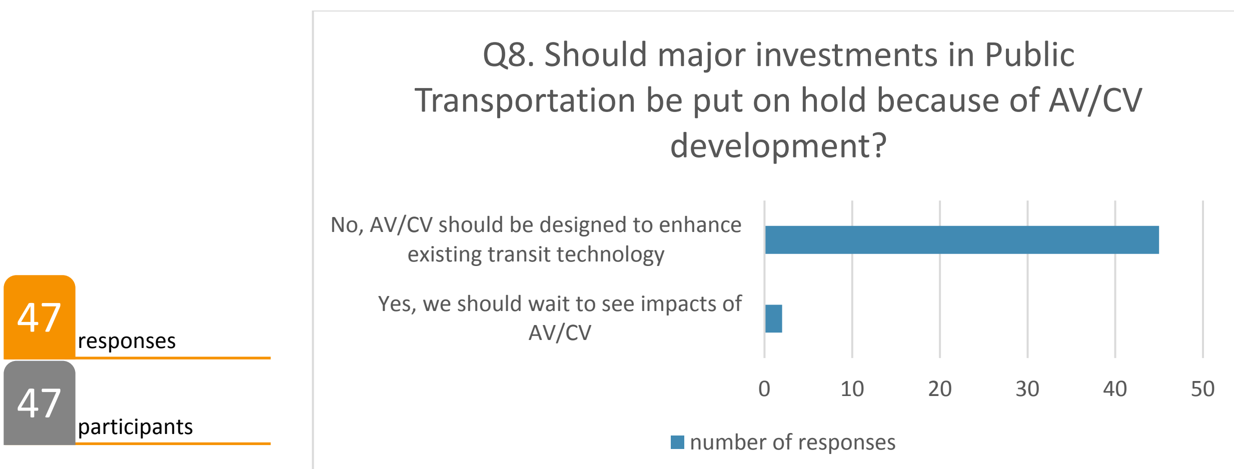


Figure 99. Effect of AV/CV Development on Public Transportation Investments.

The following discussion ensued:

> Providing more transit options may make transit more attractive to more people. The predicted sweet spot for AV car prices is $60,000. If three families shared that cost, there

might be a market for cars at that price if manufacturers sold to shared groups. Moreover, families who cannot afford that, those for whom AVs remain out of reach, may become new transit riders out of necessity. Private AV ownership may increase demand for transit from those who cannot afford a car.

Why not ask the same about the highway side? Rail has doubled what it was carrying 50 years ago but shrunk its rail mileage. Could that happen on the highway side? How did rail do it? Better technology? Consolidation? Stacked containers? Maybe shrinking headways or Uber pools are kinds of greater efficiencies. And when AV becomes concentrated enough that you don't need as much headway, you can narrow your lane width and cram more cars into the same footprint. You might not even need pavement markings if cars are determining the flow (not drivers). Actually, in Vegas there is an astounding lack of pavement markings already.

If you made major investment in very fast change that resulted in a drastic change in convenience, you would create a completely different market. You would have to think of the user in a different way.

Will automated buses increase the cost of transit? What about the needs of the elderly and disabled? If the transit function is taken over by private-sector AV operators, will they take care of those with mobility impairments? Equity is a huge issue for people with different transportation needs. Could we create an Uber voucher system for those users?

Can we build some predictability into a transit system? Develop around TODs? Design rail so it takes advantage of AV/CV?

What about emergency services and first responders? What if they did not have to fight their way through congestion to reach the injured?

Topic 4: Design Your Own Future: Scenario Planning and Automation

In this presentation, after identifying many unknowns affecting deployment of AV/CV, researchers asked participants the following:

How do you plan for such uncertainties? How is scenario planning different from alternatives analysis? Alternatives analysis relies on data of the type that we do not have about AV/CV. Scenario planning allows you to remain open to several options and build your analysis into your metrics so that you are prepared when reality starts happening. You can respond instead of react. Scenario planning asks the planner the following: What is the magnitude? What is the likelihood? You are not doing scenario planning if everyone in the room is comfortable.

Participants were then asked to respond to three polling questions. The first two focused on experiences with scenario planning and how it can help AV/CV planning in Texas; responses are summarized in Figure 100 and Figure 101.

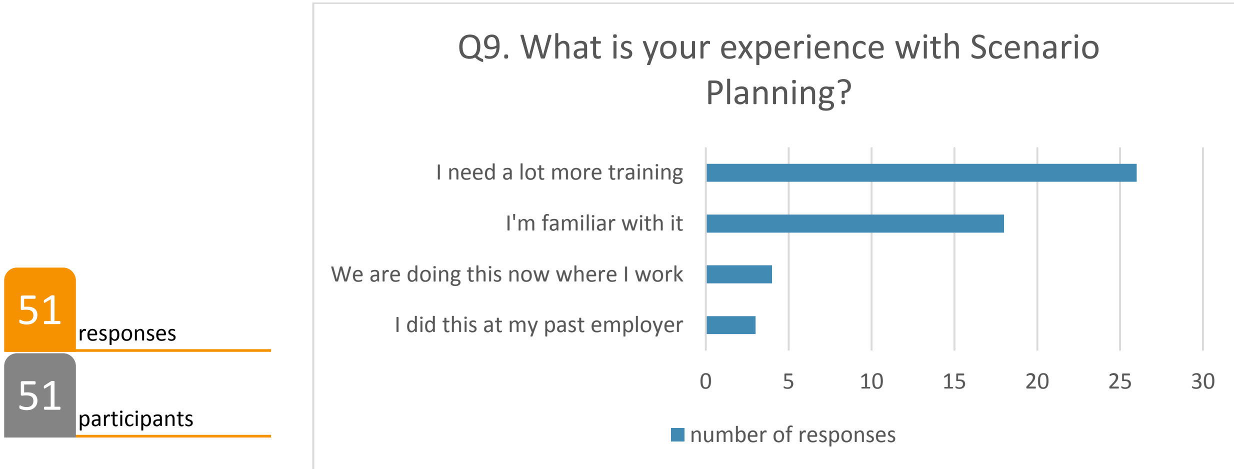


Figure 100. Experiences with Scenario Planning.

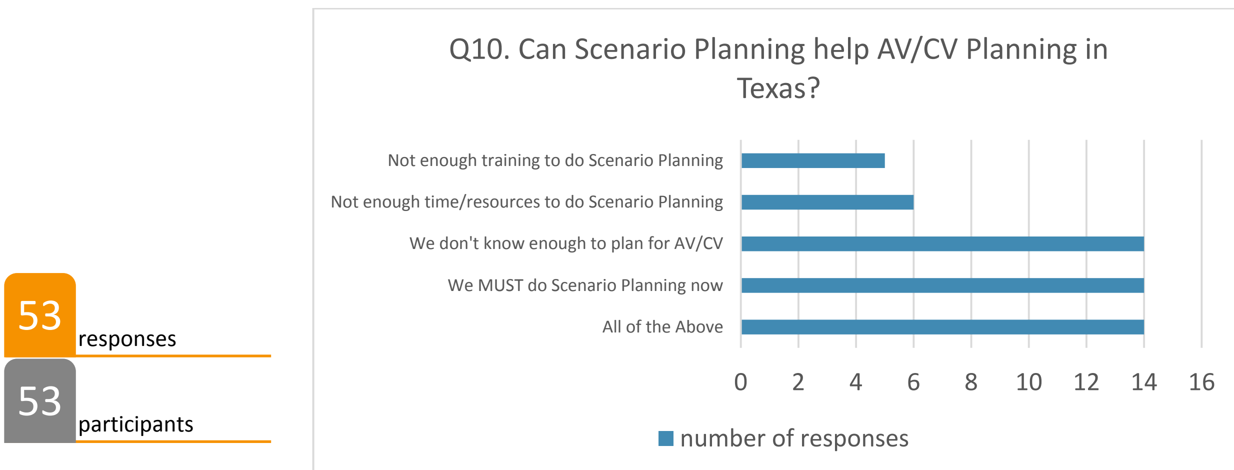


Figure 101. Feedback on Whether Scenario Planning Can Help AV/CV Planning in Texas.

The following discussion ensued based on participant responses.

> There is so much uncertainty in AV/CV; scenario planning is well suited to deal with it. We also need to understand risk. Part of it is our personality—how comfortable are we with uncertainty?
>
> Technology is getting to be more and more about AV/CV, but we still have to think about meeting capacity and demand when the market penetration is different. We can't model those scenarios or plan for them.

We are accustomed to being able to measure behavior. It is very difficult to poll people about their response to a technology they don't yet know.

Are there any discussions about public/private planning sessions? Sharing data and making long-range plans together? Data sharing is the big issue. Private players are collecting data on different platforms, and no one wants to share so that they can remain competitive. FHWA's Smart Cities initiative included a secure, open environment requirement. Uber's presentation there showed that they saw the benefit in public data too, and the value in being involved because it allows them to showcase their product.

Finally, participants were asked if planning for AV/CVs should be consistent across all regions. Figure 102 displays the results.

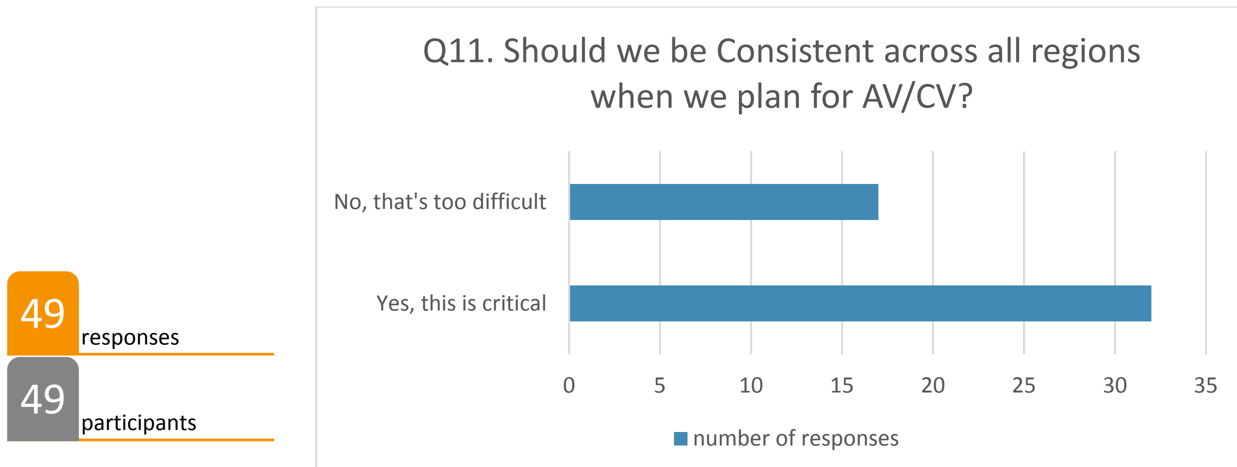


Figure 102. Feedback on the Need for Consistency in AV/CV Planning.

Following is a summary of the discussion on consistency:

Consistency is a great idea, but we know it will never happen because regions have different interests. So what will happen when one region does one thing and another does a different thing? How will that change consumer-driven decisions about traveling to different regions? From a road user perspective, we need to provide consistency from region to region.

How will we spend all these taxpayer dollars? There is so much competition between regions that the likelihood of sabotaging a region through planning style enforcement is high. And then in the middle of all that, TxDOT decides how state funding will be spent. If FHWA did another Smart Cities initiative, would they give the money to the city that did scenario planning?

If one city invests in a huge leap, will they at some point be behind the curve if other cities develop incrementally? Planning today is consistent—we use the same trip rates, demographics, forecasts. But what if people begin to consider local control, staff resource, timing issues?

Planners have a tendency to predict the biggest, worst-case scenario in order to justify their request for more funding. We're always telling you how bad it's going to be. But maybe this time we're telling you how good it's going to be.

The legal regime that makes a place friendly to technology is important, so maybe having a stable legal regime is something that everyone could agree on.

CONCLUSION

The feedback provided through the workshops was invaluable. Maintaining an awareness of AV/CVs at a regional level is very important. Leaders spend a great deal of time getting everyone up to speed at every AV/CV meeting, so one single repository for the kind of cross-pollination of information presented during the workshops would be very helpful.

CHAPTER 8. POTENTIAL IMPACTS OF AUTOMATED AND CONNECTED VEHICLES TO THE TRANSPORTATION PLANNING PROCESS

POTENTIAL TRANSFORMATION OF THE TRANSPORTATION SYSTEM

NHTSA released the *Preliminary Statement of Policy Concerning Automated Vehicles* in 2013. The statement opens with the following (*80*):

> America is at a historic turning point for automotive travel. Motor vehicles and drivers' relationships with them are likely to change significantly in the next ten to twenty years, perhaps more than they have changed in the last one hundred years. Recent and continuing advances in automotive technology and current research on and testing of exciting vehicle innovations have created completely new possibilities for improving highway safety, increasing environmental benefits, expanding mobility, and creating new economic opportunities for jobs and investment.

Each of the factors listed in this statement will have an impact on transportation plans in Texas and nationally. Improvements in safety from AV/CV technology could decrease crashes and the traffic jams they can cause. Environmental benefits from AV/CVs could change the need for legislated mandates to curb emissions so that air quality standards are met. Expanded options for mobility could change how and when people choose to travel.

Transportation planning is the process of collaboratively preparing for future events regarding the usage, location, design, impact analysis, negative effect mitigation, and investment in transportation facilities. In many instances, transportation planners can assess a future event by looking at past transportation events, choices, behaviors, and conditions that influenced the system at that time. This information is then used to forecast future conditions, usually in a manner that simply grows the conditions and behavioral response to the observed influences of the past.

However, transportation planners, collaborators, stakeholders, and decision makers are increasingly faced with the proposition that the future will be different from the past, as exemplified in the NHTSA statement. In the case of this study, the proposition under analysis was that transformational change may manifest in the future because of a significant change in vehicle, transportation system, and communications automation.

Transportation planning must rely on observations of past conditions and predictions of future conditions. However, the influence of a highly automated transportation system, even to the extent of autonomous vehicles, is expected to precipitate change that cannot be directly measured from past events. This is simply due to the fact the technology is not in operation and, while there is significant knowledge on how the technology operates and *could* be implemented in an operable environment, there is no observable behavioral response that can be currently measured.

THE FUTURE OF AV/CV TECHNOLOGY

Unlike other potential changes to transportation, the changes that may be brought about by vehicle and system automation, as being discussed by the transportation community, are potentially transformational. This means that the changes could be dramatically significant in comparison to other influences that may have relatively limited significance. AV/CV technology could increase capacity of existing roadways significantly. This condition could transform current plans for added capacity based on demand and the limitations posed by our current definition of roadway capacity.

The magnitude of potential impacts of AV/CVs to the transportation system is clear; the technology could be transformational and require significant changes to transportation plans and investment. Simultaneously, there is a lack of data-supported predictability of the impacts at this time. Although AV/CV technology is expected to have significant impacts, there are no instances where the technology can be measured as part of the existing transportation system. Although Google® has deployed its self-driving cars in both California and Austin, Texas, these vehicles are operated by Google employees in test mode. Essentially, no one in the general public can buy and be driven by an autonomous car at the present time.

Until there is significant immersion of AV/CVs into the overall vehicle fleet by the general public, there will not be any data for transportation planners to build data-supported behavioral models.

The landscape of transportation planning is different today from the past several decades. While there have been major influences and change in transportation in the past, such as with the increase in women entering the workforce in greater numbers or the decrease in household sizes, there is no paradigm to follow on the presupposed scale/magnitude and concurrent unpredictability of the impacts that a heavy or fully automated transportation system may bring. This leaves today's transportation planners with the dilemma of expecting transformation changes from technology but not being able to adequately determine the impact that the technology will have.

CROSS-MAPPING AV/CV TECHNOLOGY AND MAP-21 GOALS

The Moving Ahead for Progress in the 21st Century Act (P.L. 112-141) is the nation's transportation act signed into law on July 6, 2012. MAP-21 sets out goals for state and local transportation planning agencies, called goal areas (see Figure 103).

MAP-21 Goal Areas

- ✓ Safety
- ✓ Infrastructure Condition
- ✓ Congestion Reduction
- ✓ System Reliability
- ✓ Freight Movement and Economic Vitality
- ✓ Environmental Sustainability
- ✓ Reduced Project Delivery Delays

Figure 103. MAP-21 Goal Areas.

AV/CV technology can help significantly in achieving the goals promulgated by MAP-21. Safety is an obvious benefit that can be enhanced by AV/CV technology. AV/CVs can also address and enhance the ability to achieve significant progress toward the other goals. Infrastructure condition may improve and become automated itself, interacting with CVs. By making vehicle use more efficient, in particular trucking, the quality of infrastructure may last longer or may carry more vehicles for a longer period than otherwise.

Congestion reduction is another goal of MAP-21. Congestion is only onerous to travelers if the time spent is of no other use than to accomplish the trip itself. If the time spent traveling is put into productive use or recreational use because the driving task is automated, then the perception of congestion as a negative is eliminated. This may become one of the largest challenges to the transportation planning community. If the perception of time spent in a vehicle becomes less negative, the emphasis of long-range planning goals could shift away from reducing congestion. Planning goals may become more about satisfying the activity needs of the population and reducing efforts toward ameliorating in-vehicle travel time.

Table 24 presents a list of technologies—and associated potential behavior changes—along with potential positive outcomes on the transportation system. There are many presumptions about the potential impacts of automation technology and a move toward a mobility-as-a-service transportation environment. Each of these assumptions reflects a positive change. The assumed outcomes in Table 24 have no basis in simulation nor in any predictive modeling or observed behavior to date.

Table 24. Potential Positive Impacts of Automation and Enabled Behavioral Changes.

Technologies and Enabled Behavior	Changes to Behavior/Environment	Potential Positive Outcomes
Autonomous Vehicles	Personal Safety	Reduced Congestion
Connected Vehicles	Non-recurring Congestion	Improved Quality of Life
Mobile Workplace	Hazardous/Oversize Material Transport	Improved Public Health
Mobile Social Activity	Freight Security	Increased Personal Leisure Time
Mobile Shopping	Personal Security	Lower Cost of Mobility
Shared Cars	Expanded Mobile Population	Increased Access to Services (from Home/Business)
Shared Rides	Dynamic Workplace Choice	Increase Service Provision (to Home/Business)
Shared Bikes	Retail Shopping	Improved Air/Water Quality
Shared Desks/Offices	Commercial Land Use	Lower Greenhouse Gas Emissions
Automated Home/Office Delivery	Parking Land Use	Improved Use of Existing Infrastructure
Automated Freight Planning	Residential Location Choice	Lower Public Expense on New Infrastructure
Autonomous/Connected Trucks	Automated Vehicle Regulation	Lower Cost of Goods
Automated Container Transport	Vehicle Ownership	Lower Cost of Raw Materials
Automated Road/Network Pricing	Crash Liability	Improved Worker Productivity
Electrification	Departure Time Choice	Reduced Commute Times
Alternative Fuels	Route Speed Choice	Reduced Need for New Office Space
Transit System Automation	Expanded Tech Sector Economy	Repurposed Land Use (Parking)
Multimodal Tour/Trip Planning Automation	Fewer On-Road Vehicles	Repurposed Roadway Space
Automated Parking	Less Vehicle Idle Time	
	Empty Office Space	
	Route-Based Speed Harmonization	

SCENARIO PLANNING

Scenario planning refers to a planning process that entertains a variety of future sets of plausible conditions and puts emphasis on their probability of happening and the magnitude of impacts that each may have in store. This differs from the standard planning process that is used in most transportation planning today.

According to the FHWA scenario planning guidebook (*81*), the objective of scenario planning is as follows:

> The ultimate outcome is a shared future vision that provides a framework for transportation priorities, goals, recommendations, and investments. Through comparing scenarios and discussing their possible outcomes, the technique helps participants to

> identify and challenge assumptions about the future, discuss tradeoffs, and make better decisions.

The standard process of transportation planning focuses on trends and growth and considers only elements of the future that can be relatively reliably predicted. When faced with the knowledge of an uncertain future, scenario planning offers a different viewpoint from which to make decisions than looking at trends and predictions. The end result of the different viewpoints that scenario planning offers can be ineffective at informing current decisions. This is a condition of scenario planning that needs to be acceptable in the planning process and among stakeholders involved. However, some scenarios may provide key, but easily overlooked, information that gives decision makers invaluable insight that they would not have had otherwise. Given an uncertain future with a wide array of plausible outcomes, scenario planning offers a method to move the decision-making process forward with a higher degree of confidence than traditional best-alternatives planning.

Table 25 contrasts scenario planning with the traditional planning technique, herein referred to as "alternatives analysis." Scenario planning is designed to create several possible futures and involves key stakeholders in the process of scenario creation. Workshops are often used to accomplish this task. Participants are presented with drivers of change and are encouraged to design futures that differ from current trends. Catastrophic events are sometimes included in addition to expected but unknown and potentially transformational events. This method makes scenario planning particularly suitable for the uncertainty faced by planners today as they look at AV/CV technology.

Since impacts from AV/CVs cannot be measured and quantified at this time, scenario planning is suitable because it is designed for more descriptive potential impacts rather than measurable impacts. More assumptions are made by stakeholders in scenario creation than are typically part of alternatives analysis. In the case of AV/CVs, assumptions can be made about capacity impacts of AV/CVs that, while clearly logical, have no observed behavioral data for support.

The scenario planning process also focuses on the level of impact (magnitude) along with the probability of occurrence (likelihood) of each multiple future scenario. Sometimes these parameters can be measured, but most often, only subjective measures can be applied. Note that scenario planning is not as focused on the time frame of occurrence as alternatives analysis since the process is designed to yield information about preparatory actions rather than when action is required. Scenario planning is more focused on preparation than prediction.

The perspective on prediction is different in scenario planning versus alternatives analysis. Prediction is not as important, and it is viewed as potentially detrimental. The scenario planning viewpoint is that mistakes could be made if a prediction is seen as the absolute truth, resulting in inappropriate actions being taken when something does not turn out as expected.

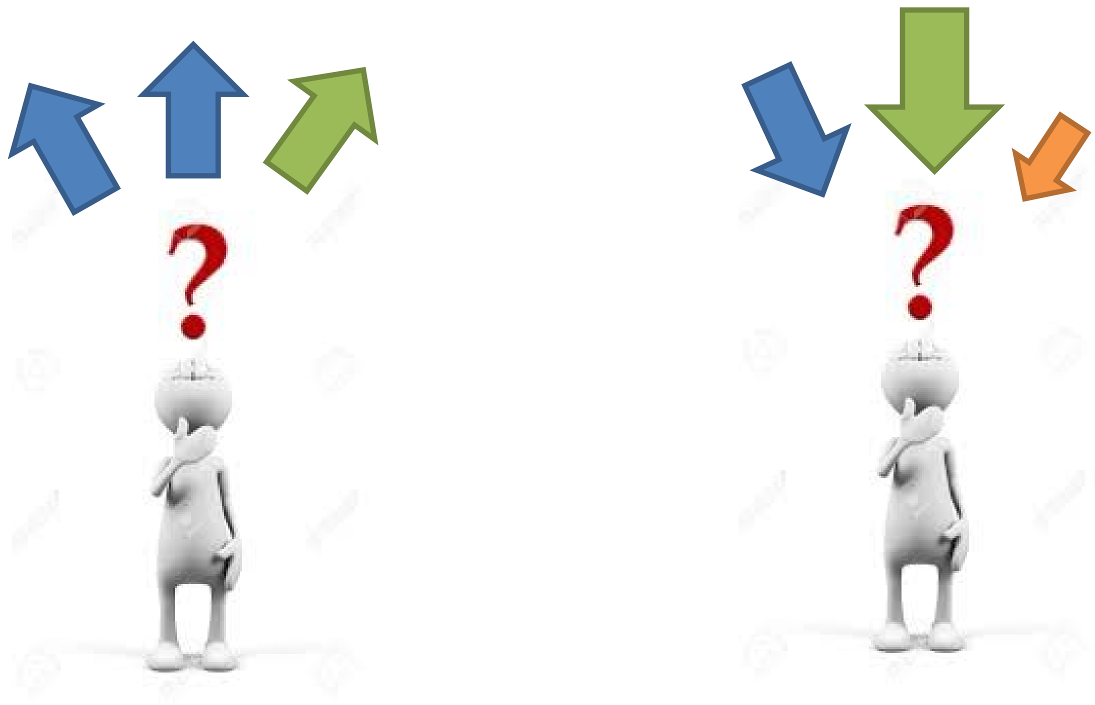
The alternatives analysis process seeks to maximize desirable benefits in one alternative, while scenario planning is geared to review and prepare actions that yield benefits to an organization no matter which scenario comes true. It is a way to prepare for the future given a high degree of uncertainty, driving current actions that eliminate the element of surprise and allowing organizations to gracefully plan for the future.

Scenario planning is also designed to entertain both strong and weak signals, if done properly. Weak signals are potential impacts that do not immediately appear to have validity given current conditions. Rather than tossing them out as not useful, scenario planning encourages that these weaker signals—with all their uncertainty—be held in contingency when considering actions. As with alternatives analysis, revisiting and reassessing the strength of indicators is a key element in the process.

Figure 104 is a schematic picture illustrating the differences between scenario planning and alternatives analysis. In alternatives analysis, the planner is tasked with designing alternatives and then choosing which one satisfies predefined performance goals. Revisiting and reassessing the chosen alternative adds some resiliency to the process, but it may be too late to adjust and respond depending on the magnitude of the decision that was made. In contrast, scenario planning involves looking at alternatives for their relative impacts and then designing a decision process that is resilient to all promulgated changes that may take place in the future. The magnitude of the decisions selected should be proportional to the expected (or predicted, if possible) likelihood and magnitude of the scenario.

Table 25. Scenario Planning vs. Alternatives Analysis.

Scenario Planning	**Alternatives Analysis**
Multiple Futures	Pick One and Stick with It
Uncertain, Descriptive	Measureable, Quantifiable
Focus on Magnitude and Likelihood	Focus on Time Frame and Trend
Reliance on Prediction Could be Detrimental	Accurate Prediction Is Assumed
Variations in Impacts, Focus on Relationships	Maximize Specifically Desired Benefits
Needs Judgement, Assessment of Impacts from Multiple Scenarios	One Decision Is Clearly Better Than Others, and Impacts from Losers Are Not Considered
Active Public Engagement	Active Public Engagement



Alternatives Analysis
Assess multiple futures,
then pick one

Scenario Analysis
Assess multiple futures,
prepare for impacts

Figure 104. Alternatives Analysis vs. Scenario Planning.

INTEGRATING SCENARIO PLANNING WITH THE TRANSPORTATION PLANNING PROCESS

Figure 105 shows the long-range transportation planning process. After establishing a regional vision and goals, planners evaluate and prioritize alternative strategies and then integrate them into a long-range transportation plan. Projects and other investments are then programmed for implementation through the transportation improvement programs. The performance of the system is evaluated and monitored, and information is fed back into the process to reassess the investment decisions.

Figure 106 shows the FHWA performance-based planning process (PBPP). This process is divided into three main components: planning, programming, and implementation and evaluation. The planning process is further divided into the two basic components of (a) goal-setting and defining performance measures to address goals, and (b) analyzing strategies and alternatives.

Figure 107 depicts how a scenario-based planning process can be used to inform the PBPP. Each step of the scenario planning process can be shown to inform each step of the PBPP. Yet, how does a planning agency integrate the two processes? Typically, many planning agencies conduct a visioning process to establish goals for the transportation plan. This process usually occurs prior to the standard planning process.

Figure 105. The FHWA Transportation Planning Process (*82*).

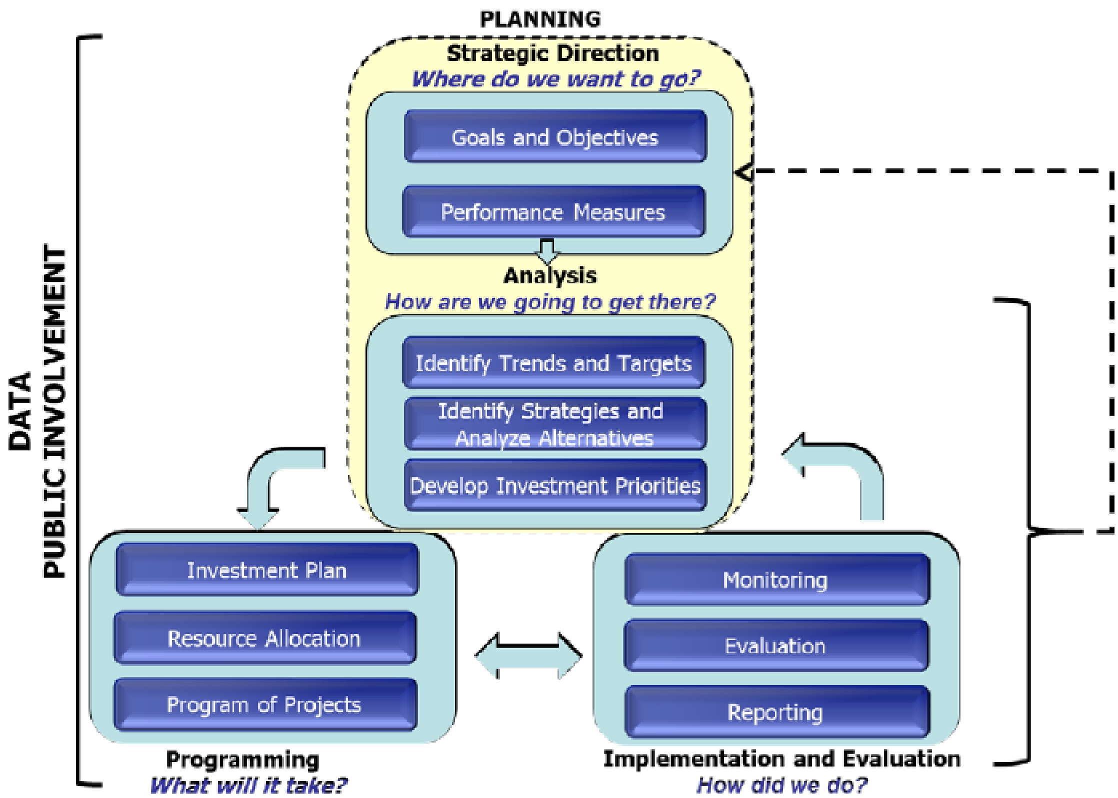


Figure 106. The FHWA Performance-Based Planning Process (*82*).

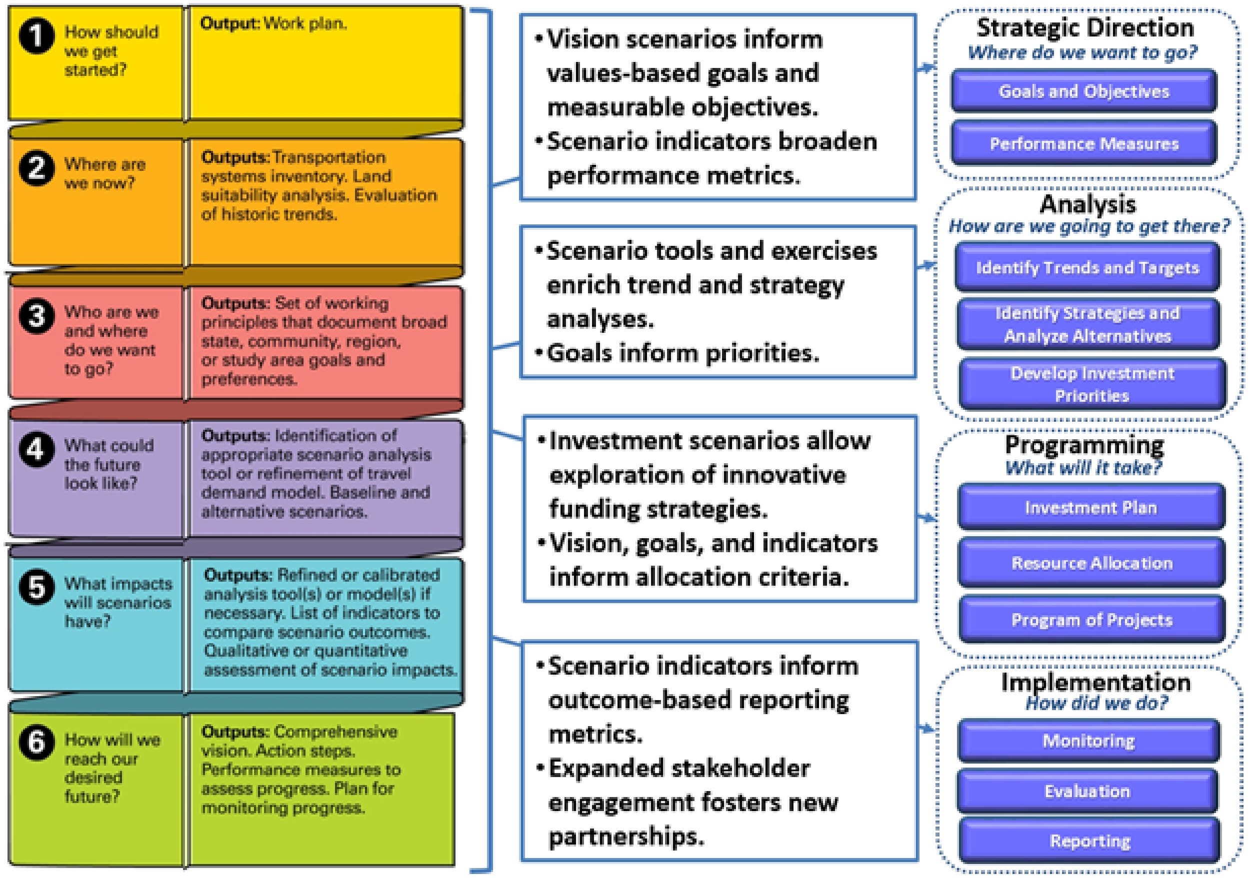


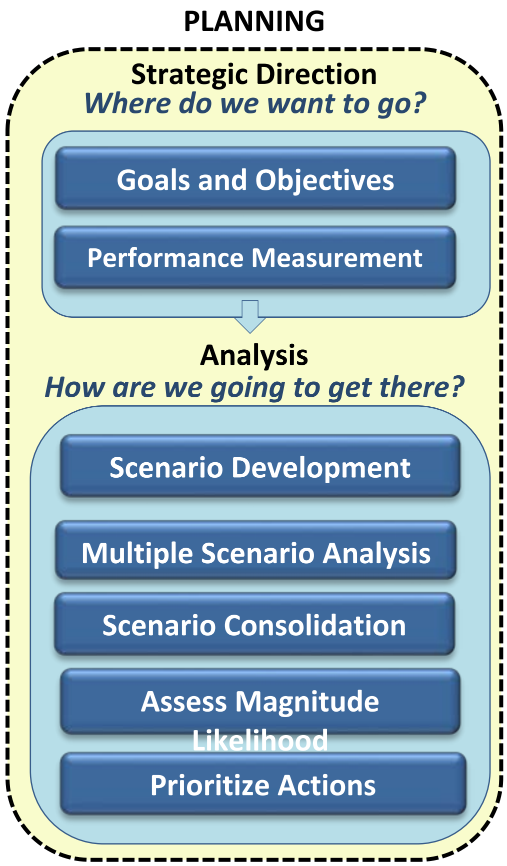
Figure 107. A Framework for Integrating Performance-Based Planning and Programming with Scenario Planning (*81*).

As an alternative to a separation of scenario planning and the standard performance-based planning process, Adapted from (*81*).

Figure 108 shows an integrated scenario–performance-based planning process.

The integrated process essentially replaces the steps within the planning box of the PBPP with the steps for scenario planning. The steps include:

1. Scenario Development—scenarios that generally address goals should be developed.
2. Multiple Scenario Analysis—all scenarios should be evaluated for their impacts.
3. Scenario Consolidation—impacts from scenarios should be consolidated into common themes.
4. Assess Magnitude—both magnitude and likelihood should be assessed.
5. Prioritize Actions—actions should be prioritized according to the likelihood and magnitude of scenario impacts.



Adapted from (*81*).

Figure 108. An Integrated Scenario–Performance-Based Planning Process.

STEPS FOR PLANNING FOR AV/CV

What actions should Texas planners take in regards to AV/CV technology in long-range plans? There are three fundamental steps planners can take to address AV/CVs:

1. Research and monitor behavioral changes and AV/CV data.
2. Forecast AV/CV impacts.
3. Perform scenario planning for an uncertain future.

Research and Monitor AV/CVs: The Data Question

Attitudes of the traveling public should be polled frequently to assess how users are perceiving AV/CVs. Over time, as the technology develops, users of the transportation system will adapt their views toward automation of the transportation system. At first, initial polls will show a lack of understanding of the technology and its impacts. As technology is deployed, familiarity with AV/CVs will grow, leading to preferences that can be measured. Eventually, monitoring of AV/CVs can move from stated preferences to revealed preferences, giving valuable market data about how users are choosing to adopt AV/CVs and related technologies.

As AV/CVs are deployed and adopted for common use by users of the transportation system, it is imperative that data be accessible to researchers, planners, TxDOT, MPOs, and other planning and implementation agencies. Integrated data systems need to be designed with three key elements in mind:

- **Policy:** Cooperatively determine which data is held privately and which data can/must be in public domain.
- **Technology:** Create transportation management centers (TMCs) and other public institutions to gather, process, and disseminate data.
- **Sharing:** Create and incentivize data sharing at all levels:
    - User—trip/tour planning.
    - Corporate—value-added services.
    - Public agency—planning, research and development.

A public policy, and perhaps regulation, that cooperatively determines which data are kept private and which data must be in the public domain is required. Since much of the technology is being researched and developed in the private sector, it is expected that data may be a product that can be traded in an open marketplace for travel. However, public agencies must look for key elements of AV/CV data that need to be shared in order to achieve public transportation goals.

As an example, several TNCs may begin using AV/CV technology in their fleets. There may be a competitive advantage created by the data the users of the TNCs create—such as location of demand for their services. A connected network may also simultaneously require the location and route plans of individual vehicles to be shared through a common TMC. The purpose of sharing the data centrally would be to gain route plans to strategically time dynamic signals in expectation of demand. This public benefit will be lost if data are not aggregated from all fleet services, such as TNCs.

Forecast AV/CV Usage and Impacts

Forecasts are needed as part of the planning process to inform stakeholders and decision makers. Since AV/CV technology will continue to be developed over time, data on behavioral response to market deployment of AV/CV technology will be collected over time to build forecasting models. While the technology is being developed and deployed, simulations and demonstrations can be performed to inform the planning process.

Below are a few steps that can be taken early as AV/CV technology is developed.

- Demonstrate capacity impacts/potential of AV/CVs:
    - Digitally using computer models.
    - With testbeds, connecting physical vehicles and infrastructure.
    - Via field testing and AI development.
- Estimate impacts with existing tools.
- Develop and implement new tools as deployment occurs.

- Perform both regional modeling and regional simulation:
  - Modeling (calibrated to observed behavioral data).
  - Simulation (scenarios imposed into modeling frameworks).

Perform Scenario Planning for an Uncertain Future of Automation

As stated earlier, scenario planning provides a method for planners to address the uncertainty of an automated personal and commercial mobility environment and associated direct and indirect impacts. Three steps can be taken to enhance the planning process in preparation for AV/CVs:

- Perform scenario planning education and training.
- Develop plausible scenarios and integrate scenario planning into standard performance-based planning.
- Coordinate common themes across regions and statewide.

Planning is a way of preparing for the future and getting the best out of it. As with all planning, ***making decisions based on past certainty when faced with knowledge of an uncertain future is folly.*** Transportation planning should immediately begin adjusting plans and processes to a future that will include automated mobility as a key element in urban systems.

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APPENDIX A. STANDARDIZED DEFINITION LIST

This research project focused on many technologies that are not yet refined or fully developed. Several do not have universally accepted or standardized terminologies, which can lead to confusion and misunderstandings. As such, the research team compiled a terminology list to serve as a reference document. The team consistently used these terms to mitigate any confusion. The list is not considered static but will be updated with new terms as needed.

Term	Acronym	Definition
Adaptive Cruise Control	ACC	An automated feature that allows an AV to travel at a set speed and adjust its speed dynamically to meet that of the traffic immediately ahead of it.
Automated Vehicle	AV	A vehicle that either wholly or partly controls the driving task, independent of direct driver input. AVs range in capabilities from no automation to full automation. When referring to vehicles with specific capabilities, the research team used the appropriate NHTSA AV levels (see below).
Basic Safety Message	BSM	A set of information transmitted to and from CVs and connected infrastructure that typically contains location information and vehicle information (like speed and acceleration).
Collision Prevention System	—	A suite of AV functions that detect, warn drivers of, and/or respond to potential crashes. Different variations on this feature help prevent front, rear, or side collisions.
Connected Vehicle	CV	Vehicles that use specialized hardware and software to send and receive information sets between each other, the infrastructure, and other modes of travel. For this report, the term connected vehicle refers exclusively to the USDOT-developed program that facilitates information exchanges to improve transportation safety, mobility, and environmental outcomes.
Cooperative Adaptive Cruise Control	CACC	ACC combined with V2V communications that enable vehicles to synchronize their acceleration and braking, decreasing following distances and improving traffic stability.
Dedicated Short Range Communication	DSRC	The CV communication range and protocol, operating on the 5.9 GHz band.
Global Positioning System	GPS	A satellite-based navigation system used for triangulating position that provides location and time information.

Infotainment	—	Commonly confused with the USDOT CV system, this term refers to any non-governmental or commercial vehicle telematics or communications systems, like those used for onboard consumer applications: navigation, weather information, music services, tolling, etc.
Light Imaging, Detection, and Ranging	LIDAR	A portmanteau of light and radar, the laser-based ranging system emits light that bounces off an object and returns to a receiver, which enables a vehicle to determine distance to an object, velocity, and other information.
NHTSA AV Levels	—	NHSTA established a series of levels that describe AVs with different amounts of functionality. The full definitions are laid out in Chapter 2. • Level 0: No Automation. • Level 1: Function-Specific Automation. • Level 2: Combined Function Automation. • Level 3: Limited Self-Driving Automation. • Level 4: Full Self-Driving Automation.
Original Equipment Manufacturer	OEM	Manufacturers and developers of automated vehicles, technologies, and related subcomponent systems.
Vehicle-to-Infrastructure	V2I	A portion of the CV communication system focused on communicating information from vehicles to infrastructure.
Vehicle-to-Other	V2X	A portion of the CV communication system focused on communicating information from vehicles to modes of transportation other than vehicles, like pedestrians, cyclists, motorcyclists, and others.
Vehicle-to-Vehicle	V2V	A portion of the CV communication system focused on communicating information from vehicles to other vehicles.

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APPENDIX C. PER-LANE HOURLY CAPACITY BY FACILITY TYPE AND AREA TYPE

Code	Facility Type	Area Type				
		1	2	3	4	5
0	Centroid Connector	49,999	49,999	49,999	49,999	49,999
1	Interstate	2170	2170	2160	2150	2130
2	Freeway	2170	2170	2160	2150	2130
3	Expressway	1170	1150	1130	1090	980
4	Principal Arterial Divided	900	890	870	840	760
5	Principal Arterial CLT	900	890	870	840	760
6	Principal Arterial Undivided	770	760	750	720	660
7	Minor Arterial Divided	810	800	780	760	690
8	Minor Arterial CLT	810	800	780	760	690
9	Minor Arterial Undivided	700	690	670	660	610
10	Collector Divided	680	670	650	640	500
11	Collector CLT	680	670	650	640	500
12	Collector Undivided	680	670	650	640	500
13	Local Divided	410	400	390	380	350
14	Local CLT	410	400	390	380	350
15	Local Undivided	410	400	390	380	350
16	Direct Connectors	1971	1971	1971	1945	1907
17	Ramp	1565	1565	1565	1544	1514
18	Frontage Road	810	800	780	760	690
19	HOV Mainlanes	2170	2170	2160	2150	2130
20	HOV Ramp	1971	1971	1971	1945	1907
21	Toll Facility 1	2170	2170	2160	2150	2130
22	Toll Facility 2—Faster Speed	2170	2170	2160	2150	2130
23	Toll—Ramp	1971	1971	1971	1945	1907
24	Toll—Direct Connector	1971	1971	1971	1945	1907

APPENDIX D. FREE-FLOW SPEEDS BY FACILITY TYPE AND AREA TYPE

Code	Facility Type	Area Type				
		1	2	3	4	5
0	Centroid Connector	15	20	25	30	40
1	Interstate	58	62	65	68	72
2	Freeway	55	60	63	68	72
3	Expressway	40	44	47	54	69
4	Principal Arterial Divided	28	38	44	55	63
5	Principal Arterial CLT	26	35	43	52	59
6	Principal Arterial Undivided	23	29	38	47	53
7	Minor Arterial Divided	25	33	39	46	59
8	Minor Arterial CLT	24	31	37	46	56
9	Minor Arterial Undivided	22	28	33	41	51
10	Collector Divided	23	28	33	43	50
11	Collector CLT	23	28	33	40	47
12	Collector Undivided	22	27	32	37	44
13	Local Divided	21	26	31	36	49
14	Local CLT	21	25	30	35	47
15	Local Undivided	20	24	29	34	45
16	Direct Connectors	45	50	55	60	65
17	Ramp	26	30	35	42	54
18	Frontage Road	37	43	47	53	58
19	HOV Mainlanes	60	60	60	60	60
20	HOV Ramp	26	30	35	42	54
21	Toll Facility 1	65	70	75	78	80
22	Toll Facility 2—Faster Speed	67	73	78	80	85
23	Toll—Ramp	26	30	35	35	42
24	Toll—Direct Connector	45	50	35	55	60

APPENDIX E. POTENTIAL IMPACTS ON TRAVEL DEMAND (H-GAC ABM MODEL)

Below are individual model components in H-GAC's recently adopted ABM. The table lists various inputs for each of the model components as well as potential sensitivities (or reactions) associated with testing AV/CV scenarios within the different input-level data. Similar to the uncertainty associated with individual trip-based stages, opposing thoughts toward other possible outcomes or reactions toward AV/CV technology can also be suggested.

Component	Input	Sensitivity to AV/CV
Population Synthesizer*		
Person-level data	Age	
	Gender	
	Worker status	Changing nature of work environment.
	Student status	Changing nature of educational environment.
Household-level variables	Income	
	Size (from person data)	
	Workers (from person data)	
	Number of children (from person data)	
	Number of children (from person data)	
Zonal Data*		
Employment by type	Parking cost	Absence of parking cost sensitivity to AVs that do not need to park.
	Density (from employment and population data)	Density could change due to changed land use, e.g., parking use conversion.
Network Level-of-Service (LOS) Data*		
Location of transit stops	Time-of-day (TOD) travel time/distance	Travel times reduced.
	TOD toll	Tolling rates decrease in response to reduced congestion? Automated tolling sensitivity to occupancy rates, automated in shared AVs.
Vehicle Availability		
	Number of children 16+	Absence of labor cost in a robo-taxi mobility environment may make this new mode highly cost effective. Lowered cost of vehicle travel may increase auto (robo-taxi) availability, increasing probability of choosing AV mode over personal vehicle or public transportation.
	Number of adult students	
	Number of full-time and part-time workers	
	Number of non-working adults and seniors	
	Household size	
	Household income	
	Household composition	
	Presence of transit stops within walking distance	
	Mixed-use density	

	Ratio of peak auto to transit accessibility to employment	As this ratio increases, auto accessibility would likely result in a higher vehicle availability.
No Regular Workplace		
Socioeconomic data	Age	
	Gender	
	Worker status	
	Household income	
	Number of workers	
	Number of children	
	Number of vehicles	Increases in number of auto vehicles would likely result in more persons with regular workplaces.
	Mixed-use density in home zone	
Usual Work Location		
Employment by type	College enrollment	
	Number of households	
LOS variables	Distance (roundtrip)	
	Intra-zonal variable	
	Work tour mode choice model logsum	Any move toward proportionally more auto modes may result in more dispersed work locations.
School Location		
	Distance (roundtrip)	
	Transit access (children only)	
	K-12 employment, K-12 enrollment	
	Office employment (child type 1 only)	
	College employment (child type 5 only)	
	Number of households	
	Zero-car household	Zero-car households more sensitive to distance in terms of location. Fewer zero-car households could increase school location distance.
	Household composition	
	School location of younger children	
Daily Activity Pattern (DAP)		
Socioeconomic data	Number of household members by person type	
	Household income	
	Number of vehicles	
	Gender	
	Age	
	Mixed-use density of household zone	
LOS variables	Presence of transit stop within walking distance of household zone	

	Highway accessibility to employment	
Variables from other models	Presence of regular work place	Increases in regular workplaces means increased likelihood of work tour generation.
	Mode choice logsum to regular workplace	
	Number of cars in household	As this increases, there is a likely decrease in fewer stay-at-home patterns.
Interaction variables	Workers > cars	As variable moves to false (binary variable), there is a decreased likelihood of stay-at-home patterns.
School Escorting		
Escort characteristics	Gender	
	Person type	
	Full- or part-time worker over 50	
	Daily activity pattern	
LOS attributes	Transit accessibility indicator between home and school	
	Generalized time between home and school	As this decreases, there is an increased likelihood of school escorting.
	Detour generalized time	As this decreases, there is an increased likelihood of school escorting.
School tour attributes	Presence of child less than 5 years in the child group	
	Presence of child 16 years or more in the child group	
	Age of the youngest child in the child group	
	Group size 2 or more indicator	
Household characteristics	Zonal mixed-use density	
	Child < 5 in household with stay-at-home DAP	
	Zero-car household?	If this variable proves false (binary variable), then there is a higher likelihood of school escorting.
	Income	
Interaction variables	Workers > cars	If this variable proves false (binary variable), then there is a higher likelihood of school escorting.
Joint Tour Generation		
LOS variables	Highway accessibility	As this increases, there is an increased likelihood of joint tours.
TAZ variables	Presence of transit stops within walking distance	
Socioeconomic data	Number of household members (segment by person type [PT], i.e., child, full-time worker, university student, non-working adult, senior, etc.) and DAP type; the Houston ABM generates 8 PTs from the population synthesizer	
	Household income	

	Household composition	
	Vehicle availability	As this increases, likelihood of multiple joint tours decreases.
Variables from other models	Time window overlaps among household members	
	DAP among household members	Increase in non-mandatory only patterns results in increased likelihood of joint tours.
Interaction variables	Workers > cars	If choice moves to false, there is a likelihood of certain types of joint tours decreasing.
Non-mandatory Tour Generation		
LOS variables	Ratio of highway/transit accessibility to employment	
	Highway accessibility to total employment	Increased accessibility increases likelihood of tours.
Socioeconomic data	Total employment	
	Employment by type	
	Employment density	
	Household size	
	Household income	
Interaction variables	Workers > cars	
Variables from other models	Number of vehicles in household	Increases lead to increased likelihood of tours.
	Time availability	Increases lead to increased likelihood of tours.
Tour-level attributes	Number of persons with mandatory DAPs	As this increases, there is likelihood that this leads to increased escort tours.
	Number of workers with non-mandatory DAPs	As this decreases, there is a decreased likelihood of tours.
	Number of school escorting tours	Increases lead to increased likelihood of tours.
Work Sub-tour Generation		
Socioeconomic data	Highway accessibility to employment	As this increases, likelihood of sub-tours increases and likelihood of additional travel increases.
	Distance from home to work	As this increases, likelihood of sub-tours decreases and likelihood of additional travel decreases.
Tour-level attributes	2 or more work tours	
	Number of personal business and fully joint tours	
	Mode of primary tour	As modes move to auto, likelihood of sub-tours increases and likelihood of additional travel increases.
Tour Destination		
LOS variables	Distance	As this increases, likelihood of choosing as destination decreases.
	Transit accessibility	As this increases, likelihood of choosing as destination increases.
Socioeconomic data	Mixed-use density (home zone)	

	Employment by type	
Variables from other models	Mode choice logsum	Reduced congestion increases likelihood of TAZ being chosen as destination.
	Usual work place (for work tours)	As utility for usual workplace (work tours) increases, likelihood of choosing as destination increases versus non-regular workplace.
Tour TOD Choice		
Socioeconomic data	Person type	
	Gender	
	Age	
	Number of children	
	Household income	
LOS variables	Auto time (roundtrip—full tour)	Decreased time decreases likelihood of shifting out of peak.
	Delay	Decreased delay increases likelihood of traveling in peak of peak.
Variables from other models	Tour type	Move to mandatory (i.e., work) tours means more travel in peaks.
Stop Generation		
Socioeconomic data	Vehicle availability	Increased availability decreases number of stops, which could mean more stand-alone tours.
	Household income	
	Person type	
	Age	
	Gender	
	Mixed-use density and employment density at destination	
LOS variables	Roundtrip auto distance	Increased distance to primary activity equates to more stops for all tour purposes. Reduced stand-alone tours and travel.
	Ratio of drive-alone to walk to transit time	Reduced auto travel time would result in a decrease in this ratio, which would decrease the likelihood of stops of some purposes and increases in others, but generally result in decreased likelihood of multiple stops on a tour. More stand-alone tours.
Interaction variables	Worker > cars	As this variable moves to false, the likelihood of escort stops decreases and escort-only tours increases. Provides opportunity for non-mandatory travel.
Tour Mode Choice		
Socioeconomic data	Household income	
	Gender	
	Age	
	Number of workers	

	Number of children	
	Household size	
	Vehicle availability	Increases lead to increased likelihood of auto, particularly drive-alone mode.
	Number of students	
	Mixed-use density at end of tour	
	Population density at destination	
LOS variables	Cost	
	In-vehicle travel time	Decrease leads to increased likelihood of auto modes.
	Out-of-vehicle travel time	Decrease leads to increased likelihood of auto modes.
	Roundtrip distance	As this increases, there is a decreased likelihood of bike, walk.
Tour characteristics	Tour purpose	Work tours more likely to be drive-alone mode.
	Number of stops	Increases lead to increased likelihood of auto mode.
	Number of joint or work tours in DAP	Increases lead to decreased likelihood of walk and shared-ride mode.
	Child escorted to/from school	Decreases lead to increased likelihood of drive-alone mode.
Interaction variables	Zero-car households	As this decreases, there is an increased likelihood of auto modes.
	Workers > cars	As this decreases, there is an increased likelihood of drive-alone mode.
	Adults > cars	As this decreases, there is an increased likelihood of drive-alone mode.
Stop Destination Choice		
Socioeconomic data	Income	
	Worker type	
	Zonal employment by type	
	College enrollment	
	Number of households	
LOS variables	Detour accessibility	Lower travel time and detour accessibility increases potential as a stop location. Potentially more dispersed stops.
	Highway and transit travel time	
Stop Time-of-Day Choice		
Socioeconomic data	Person type	
LOS variables	Distance	
	Detour distance	
Tour characteristics	Tour purpose	If work tour, there is a likelihood of longer stops and less opportunity for additional travel.
	Tour mode	Drive-alone mode shortens stop duration. Shorter stop duration leaves more time for additional travel.

	Tour duration	If longer tour, there is an increased likelihood of longer stops and thereby less opportunity for additional travel.
	Tour arrival/departure period	
Stop characteristics	Stop purpose	
	Presence of additional stops to be modeled	
Trip Mode Choice		
Socioeconomic data	Household income	
	Gender	
	Age	
	Person type	
	Number of children	
	Vehicle availability	Higher value increases the likelihood of drive-alone and decreased transit, shared-ride, and non-motorized modes.
	Household size	
	Employment density at each end of tour	
Tour characteristics	Tour purpose	
	Tour mode	Trip mode usually same as tour mode, so more auto mode tours means more for auto mode trips.
	Fully joint tour group size	
	Number of stops	
Sequence	Sequence of trip on tour (first or last)	

* Not an ABM component, but one that provides data to the ABM.

APPENDIX F. SELF-DRIVING VEHICLE SURVEY

You are being invited to take part in a research study, which includes an online survey conducted by the Texas A&M Transportation Institute (TTI) and funded by the State of Texas. The purposes of this study are to examine the factors that might influence people's future use of self-driving vehicles and how high levels of vehicle automation could affect the ways in which people will choose to travel in the future. This survey will take about 10 minutes to complete.

The questions that you will be asked to answer pose no more risks to you than you would come across in everyday life. Your participation is entirely voluntary, and you can refuse to take part at any time. If you decide you do not want to participate, there will be no penalty to you, and you will not lose any benefits you normally would have. Aside from your time, there are no costs for taking part in the study.

Information about you and related to this study will be kept confidential to the extent permitted or required by law. No identifier linking you to this study will be included in any sort of report that might be published. Information about you will be stored in computer files protected with a password. People who have access to your information include the principal investigator and research study personnel. Representatives of regulatory agencies such as the Office of Human Research Protections (OHRP) and entities such as the Texas A&M University Human Subjects Protection Program may access your records to make sure the study is being run correctly and that information is collected properly.

You may contact TTI researcher Dr. Ipek N. Sener for study details or to tell her about a concern about this research at 512-407-1119 or i-sener@tti.tamu.edu. For questions about your rights as a research participant, to provide input regarding research, or if you have questions, complaints, or concerns about the research, you may call the Texas A&M University Human Subjects Protection Program office by phone at 1-979-458-4067, toll-free at 1-855-795-8636, or by email at irb@tamu.edu.

If you would like to take part in the study, please continue by clicking the "Next" button below.

Q1. What is your age?

Q2. Do you live in Texas?

- Yes (Skip to Q3)
- No

Q3. In what zip code do you live? Please select from the following drop down menu.

Q4. What is your gender?

- Male
- Female
- Other

Q5. Do you have any physical conditions that prohibit you from driving?

- Yes (please specify)
- No

Q6. How well do the following statements describe you? (5-level scale: "very untrue of me," "somewhat untrue of me," "neutral," "somewhat true of me," and "very true of me")

- I enjoy making my own decisions.
- I prefer to do something about a problem than to sit by and let it continue.
- I would rather someone else took over leadership role on a group project.
- When it comes to orders, I would rather give them than receive them.

Q7. How much do you agree or disagree with the following statements? (5-level scale: "strongly disagree," "somewhat disagree," "neither agree nor disagree," "somewhat agree," and "strongly agree")

- It is important to keep up with the latest trends in technology.
- New technology makes people waste too much time.
- New technology makes life more complicated.
- Technology will provide solutions to many of our problems.

Q8. How often do you use the following technologies? (5-level scale: "never," "several times few times a year," "several times a month," "several times a week," "several times a day," and "several times an hour") (If "never" to all options, skip to Q10)

- Smartphone usage
- Facebook usage
- Internet shopping
- Other Internet searching
- E-mailing
- Text messaging
- Video gaming
- Smartphone transportation apps

Q9. To what degree do you have data privacy concerns about using online technology?

- Not at all concerned
- Somewhat concerned (in some situations)
- Moderately concerned (in most situations)
- Extremely concerned (in all situations)

Q10. When it comes to adopting new technology, in which category do you fall on the adoption curve—early adopter, late adopter, or laggard?

- Early adopter—I am among the first of my friends to adopt new technology.
- Late adopter—I wait awhile before adopting new technology.
- Laggard—I am among the last of my friends to adopt new technology, if I adopt at all.

Q11. Do you currently own or lease a vehicle?

- Yes—I currently own or lease a vehicle.
- No—I do not own or lease a vehicle. (Skip to video)

Q12. Does the vehicle that you currently own or lease have automated features, such as adaptive cruise control, automated lane keeping, or automated parking systems?

- Yes
- No

In our study, we are interested in your opinions about self-driving vehicles. You may be able to buy a self-driving vehicle from major manufacturers or access one through a car-sharing service within the next 5-8 years. A self-driving vehicle is a vehicle that controls all driving functions for an entire trip, including steering, braking, and acceleration. It covers freeway driving, neighborhood driving, and activities like parking. The "operator" provides destination or navigation input, and is in the vehicle to take over control of the vehicle if conditions warrant. The market push for self-driving vehicles is to make driving safer and more efficient. Please watch the following video on self-driving vehicles before continuing with the next questions: https://www.youtube.com/watch?v=cdgQpa1pUUE

Q13. Have you ever heard of self-driving vehicles before participating in this survey?

- Yes
- No
- Don't know

Q14. How well do the following statements describe you? (5-level scale: "very untrue of me," "somewhat untrue of me," "neutral," "somewhat true of me," and "very true of me")

- I would find self-driving vehicles useful in meeting my driving needs.
- If I were to use self-driving vehicles, I would feel safer on driving trips.
- I would be proud if people saw me using a self-driving vehicle.
- People whose opinions I value would like using self-driving vehicles.

Q15. How well do the following statements describe you? (5-level scale: "very untrue of me," "somewhat untrue of me," "neutral," "somewhat true of me," and "very true of me")

- I have concerns about using self-driving vehicles.
- Self-driving vehicles are somewhat frightening to me.
- Learning to operate a self-driving vehicle would be easy for me.
- Interactions with self-driving vehicles would be clear and understandable to me.
- It would be easy for me to become skillful at using self-driving vehicles.

Q16. How much do you agree or disagree with the following statements? (5-level scale: “strongly disagree,” “somewhat disagree,” “neither agree nor disagree,” “somewhat agree,” and “strongly agree”)

- Using a self-driving vehicle is a good idea.
- Self-driving vehicles make driving more interesting.
- Using a self-driving vehicle would be fun.
- Using a self-driving vehicle would decrease accident risk.

Q17. Imagine that self-driving vehicles were on the market now for either purchase or rental. What is the likelihood that you would ride in a self-driving vehicle for everyday use?

- Not at all likely
- Somewhat unlikely
- Somewhat likely (Skip to Q19)
- Extremely likely (Skip to Q19)

Q18. What is the main reason you would be unlikely to ride in a self-driving vehicle for everyday use?

- Safety
- Cost
- Insurance/liability
- Lack of trust in technology
- Other (please identify)

Q19. What is your current level of employment?

- Employed full-time
- Employed part-time
- Not currently employed (Skip to Q22)
- Retired (Skip to Q22)

Q20. How did you usually get to work last week? The single mode of travel used for the longest distance for your primary job.

- Vehicle driver
- Vehicle passenger
- Public transit
- Walk (Skip to Q22)
- Bike (Skip to Q22)
- Telecommute (work at home) (Skip to Q22)

Q21. Is this a vehicle owned by …..

- Your household
- A friend or relative
- Car-sharing service (e.g., Zipcar, Car2go)
- Ridesharing service (e.g., Carma, Carpooling, Ridejoy)
- Taxi service (e.g., Uber, Yellow Cab)

Q22. Are you a full or part-time student?
- Full-time student
- Part-time student
- Not a student (Skip to Q25)

Q23. How did you usually travel to school last week? The single mode of travel used for the longest distance each day.
- Vehicle driver
- Vehicle passenger
- Public transit
- Walk (Skip to Q25)
- Bike (Skip to Q25)
- Telecommute (online school) (Skip to Q25)

Q24. Is this a vehicle owned by …..
- Your household
- A friend or relative
- Car-sharing service (e.g., Zipcar, Car2go)
- Ridesharing service (e.g., Carma, Carpooling, Ridejoy)
- Taxi service (e.g., Uber, Yellow Cab)

Q25. Including yourself, how many individuals live in your household?
- One
- Two
- Three
- Four or more

Q26. How many children less than 16 years of age live in your household?
- None
- One
- Two
- Three or more

Q27. How many motor vehicles does your household own or lease?
- None
- One
- Two
- Three or more (Skip to Q29)

Q28. Which of the following reasons best describes why you don't own or lease a motor vehicle?
- Affordability of purchase price
- Ongoing operational/maintenance costs
- Lifestyle needs met by walking, biking, and other transportation options
- Can't drive—for whatever reason
- Other

Q29. Do you have a current driver's license?

- Yes
- No

Q30. Did you use any of the following transportation services last week? (select all that apply)

- Carsharing services, like Zipcar or Car2go
- Ridesharing services, like Carma, Carpooling, or Ridejoy
- Taxi services, like Uber or Yellow Cab
- Transportation apps, like Waze, Roadify, Metropia, Ridescout, Google Maps
- Public transit services, either bus or rail
- Transportation service for senior or disabled
- None of the above

Q31. How often do you drive a motor vehicle?

- Every day
- A few days a week
- A few days a month
- Almost never

Q32. About how many miles did you drive in 2014?

- Less than 5,000
- 5,000 to 10,000
- 10,000 to 15,000
- More than 15,000

Q33. What is the highest degree or level of school you have completed?

- Grade 12 or less (1)
- High school graduate (2)
- Associate's degree or some college (3)
- Bachelor's degree (e.g., BA, BS) (4)
- After bachelor's degree (e.g., MA, MS, MD, JD, Ph.D.) (5)

Q34. What category best describes your total household income for last year?

- Less than $25,000
- $25,000 to $49,999
- $50,000 to $99,999
- $100,000 to $149,999
- $150,000 or more

Q35. How much did viewing the video influence your intention to use a self-driving vehicle?

- Extremely
- Somewhat
- Not at all

Q36. The project team is interested in conducting a follow-up study on future travel behaviors. Would you be interested in participating in a face-to-face interview as part of this potential study? Your time will be compensated.

- Yes
- No