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16. Abstract
This project assesses how Texas roadway and parking infrastructure should evolve as connected and automated vehicles (CAVs) gain market share, using behavioral-diffusion insights to frame adoption scenarios. Researchers combined literature synthesis with expert questionnaires/interviews, analysis of AV disengagement reports, and PTV Vissim microsimulations of lane and parking layouts under varying CAV penetration. Results show that sight-distance standards, shoulder and clear-zone widths, lane and curb-parking widths, and speed-change-lane lengths are the most sensitive geometric elements, and that platooning permits 10–20 % narrower travel lanes—about 2.4 m (8 ft)—without degrading the level of service. Experts stress that uniform high-contrast pavement markings, lane-by-lane signal heads, and robust digital-map support are prerequisites for machine vision and recommend extended dotted merge lines plus left-turn lane-marking extensions to mitigate localization issues at ramps and intersections. The report advises transportation agencies to update geometric-design and parking manuals to adopt these narrower AV-compatible lanes, strict marking maintenance, and flexible parking footprints, enabling planners to reclaim right-of-way for transit, cycling, and green infrastructure as CAV adoption accelerates.

17. Key Words
Connected and Automated Vehicles (CAV), Traffic Flow, Geometric Design

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Develop Roadway and Parking Design Criteria to Accommodate Automated and Autonomous Vehicles

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DISCLAIMER

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Glossary of Acronyms and descriptions

ABBREVIATIONS	MEANING
AASHTO	American Association of State Highway and Transportation Officials
ACC	Adaptive Cruise Control
ADA	Americans with Disabilities Act
ADAS	Advanced Driver Assistance System
ADS	Automated Driving System
ADT	Average Daily Traffic
AV	Automated Vehicle
CACC	Cooperative Adaptive Cruise Control
CAV	Connected Automated Vehicle
CBD	Central Business District
COV	Coefficient of Variation
CVs	Connected Vehicles
DDT	Dynamic Driving Task
DSD	Decision Sight Distance
EB	East Bound
EVs	Electric vehicles
FHWA	Federal Highway Administration
GHG	Greenhouse Gas
GPS	Global Positioning System
HDV	Human Driven Vehicle
HMETC	Hyundai Motor Europe Technical Center
HOV	High Occupancy Vehicle
IOOs	Infrastructure Owner Operators
ISD	Intersection Sight Distance
ITS	Intelligent Transportation System
Lidar	Light Detection and Ranging
LKA	Lane Keeping Assist
LOS	level-of-service
MAPE	Mean Absolute Percent Error
MPR	Market Penetration Rates
MUTCD	Manual on Uniform Traffic Control Devices
NACFE	North American Council for Freight Efficiency
NCHRP	National Cooperative Highway Research Program
OD	Origin Destination
ODD	Operational Design Domain
OEDR	Object and Event Detection and Response
OEDR	Object Event Detection Response
OEMs	Original Equipment Manufacturers
PAVs	Private Automated Vehicles

PROWAG	Pedestrian Facilities in the Public Right-of-way
PSD	Passing Sight Distance
Radar	Radio Detection and Ranging
RDM	Roadway Design Manual
ROW	Right of Way
SAE	Society of Automotive Engineers
SAEVs	Shared Autonomous Electric Vehicles
SAVs	Shared Autonomous Vehicle
SPaT	Signal Phasing and Timing
SSD	Stopping Sight Distance
TAZs	Traffic Analysis Zones
TCDs	Temporary Traffic Control Devices
THFN	Texas Highway Freight Network
TLC	Traffic Light-Controlled
TMUTCD	Texas Manual on Uniform Traffic Control Devices
TOC	Traffic Operation Center
TPWD	Texas Parks and Wildlife Department
TransAID	Transition Areas for Infrastructure-Assisted Driving
TSRS	Traffic Sign Recognition System
TxDOT	Texas Department of Transportation
V2C	Vehicle to Cloud
V2I	Vehicle to Infrastructure
V2P	Vehicle to Pedestrian
V2V	Vehicle to Vehicle
V2X	Vehicle-to-everything
VMT	Vehicle Mile Traveled
WB	West Bound
WTP	Willingness to Pay

Executive Summary

With the emerging concept of autonomous vehicles (AV) and more importantly connected autonomous vehicles, there has been tremendous research focus on understanding the factors that influence their adoption. Analysis of market penetration is beneficial in creating economic forecasts that are relevant to auto industries and other supporting industries. It is anticipated that Connected and Automated Vehicle (CAV) market penetration will significantly impact such forecasts and outcomes. Also, understanding the market penetration of CAV will enable planners in making decisions for infrastructure needs for CAVs. The role of different behavioral theories along with the diffusion models in estimating the market share has been presented in various studies. The impacts of certain attributes such as trust in technology, perceived benefits and concerns, and attitude on the adoption of AVs have also been analyzed in literature. The current road infrastructure is built for human drivers and there is a need to improvise to accommodate for AVs. At present, semi-autonomous vehicles are available in the market, and they are equipped with various types of sensors, active safety systems, and driver-assist systems. AVs rely on visual detection and interpretation for movement. Hence, road markings and traffic signs play a vital role in the future of AVs. They must be developed and updated as per the requirements of AVs. At first the current study explored on various changes that shall be required in roadway design manual to accommodate AVs, further the study explored on various infrastructural modifications that can be beneficial to incorporate AVs, and finally the study investigated on various parking guidelines that are important to be explored further to make necessary changes.

Geometric design of highways and streets includes the calculations and analysis made by the designers to provide the road alignment with the required safety and level of service for a given terrain. The geometric design of roads is a function of the design vehicles, human factors, design speed, and traffic characteristics. Currently, roads are designed, built, and maintained for vehicles controlled by a human driver, and the geometric design of the road is performed considering that a human driver is operating the vehicle. Highway's geometric design elements are addressed considering horizontal and vertical alignment and are driven by sight distances (currently influenced by the human element and tire pavement interaction) and vehicle performance associated highway geometric elements such as slopes, superelevation, horizontal and vertical curves, carriageway width, design speed, and other roadside features to have safe and efficient road transportation. These factors are different for human-driven vehicles and autonomous vehicles as these factors depend on the perception by the human brain and associated decision making. The significant difference between AV technology and the human-driven vehicle in terms of sight distance presents opportunities for optimization of current road geometrics design standards. Design of geometric elements to accommodate AV, looking from the perspective of AV, would need to consider the operational characteristics of vehicles in automation mode in specific operation design domains as well as safety of the passengers and other road users. Roads are currently being designed based on human drivers' limitations, such as reaction time, sight distance, and human errors in evaluating the position of other vehicles. As expected, and subjected to additional field testing of AVs, the minimum values of geometric design parameters required for a human-driven vehicle are higher than for AVs. Hence, for this purpose, two scenarios are considered, one with dedicated AV lanes and the other without dedicated lanes, and modifications are proposed for each scenario based on the existing literature. Design

elements such as sight distances, width of shoulders and clear zones, curb parking widths are identified as the most crucial elements which require attention for both scenarios. Also, when dedicated lanes are provided design speed, width of lanes, length of speed change lanes is impacted which further influences the horizontal and vertical alignment of roadways.

Another important objective of this study was to provide valuable insights regarding the impacts of automated vehicle (AV) technology on roadway infrastructures. The first step of the study was to develop a questionnaire that covered most of the aspects relevant to an AV future. The subsequent step was to identify and contact the experts in relevant fields for a video interview or questionnaire survey. Various elements of roadway infrastructure (traffic signs, traffic signals, digital maps, urban intersections, entrance and exit ramps, work zones, active transportation modes (walk, bike), roadside barriers, etc.) were discussed and appropriate recommendations were obtained. The majority of the experts agreed that markings and signages are critical in the deployment of AVs. Various challenges and findings were reported, and suitable recommendations were formulated. A decisive aspect of pavement markings and signages is that they need to be uniform, well maintained, and must have sufficient visibility in all conditions. Therefore, experts stressed upon having a minimum performance criterion for these vital elements, especially for pavement markings. Another important aspect that is crucial for AVs is having a sustainable combination of digital maps and machine vision. Further, to understand the challenges faced by AVs disengagement reports were examined and selected challenges that were deemed related to infrastructure were further investigated and possible alternatives were explored. One of the findings was that merge sections were found to produce issues in AV's localization, at the entrance and exit ramps. Experts recommended that having extended dotted lines can mitigate this issue and certainly helps in the manoeuvrability of AVs. Similarly in urban intersections having lane marking extensions for left turn movements was expressed to be critical by experts. In addition, another aspect where AVs are too conservative is stop sign controlled intersections and it was found that possible infrastructural modifications are limited at such locations. A potential solution to this challenge is V2I and V2V connectivity that can alleviate the situation and smoothen the operation.

Another aspect that was investigated was the consistency of positioning traffic signals, experts believed that it is not possible to have a uniform position of traffic signals or consistent placement position of traffic signals with respect to pavement surface due to numerous reasons. However, they resonated about the importance of having a signal head in each lane to provide better communication with AVs. When asked about having a classified roadway system the views of the experts varied owing to multitude of challenges in this domain. Another challenging maneuver for AVs is to navigate around the work zones, various alternatives were included and evaluated. Further, certain elements of bike infrastructure and roadside barriers were also explored and are reported in this document.

As parking concerns continue to grow in cities and urban regions, advances in parking technology are being made to accommodate the transition to self-driving vehicles. This transition will most likely take some time and involve a mix of both human-driven and Autonomous Vehicles (AV). The movement of 'self-driving' vehicles are controlled by a sophisticated system of sensors, cameras, radars, and lidars (a sensor technology that employs light). Because they can react quicker and maneuver more smoothly than human drivers, these AVs may move closer together on narrower routes. Some space will be freed up by more efficient driving patterns, but what will really make a difference is integrating AVs with vehicle sharing and innovative techniques for parking and maintaining automobiles. This study provides a summary of the design considerations and recommendations considering mixed traffic scenarios. The research team used microsimulation tools (PTV Vissim), video analysis of user experiences, and focused information search to more precisely summarize the essential design criteria that needs modification and summarize additional new attributes that designers, engineers, planners, or current or potential parking landowners should take into consideration while retrofitting or redesigning existing parking infrastructure. To comprehend the effects of AV on street parking under various market penetration scenarios, micro-simulation analyses were carried out, specifically examining the cross-sectional width requirements for parking lanes and traffic lanes. The study used three different forms of analysis to determine how AVs might affect the parking designs that were already in place. All the vehicles on the road could fit into far less space if they were all autonomous. AV might go closer together without worrying about colliding with one another in the rear. The vehicles themselves may be smaller and thinner, occupying less space, if collisions decreased in frequency. With little to no impact on travel times, city planners could narrow roadways or even reduce the number of lanes. Lanes designated for autonomous vehicles will not need to be wider to account for human error. If vehicle dimensions essentially remain constant, lane width could be reduced by up to 20%, for a width of about eight feet, to be closer to real vehicle width. Because they deter unsafe driving behavior and reduce vehicle speeds, decreases of even ten feet in the space between conventional vehicles, pedestrians, and bicyclists could be advantageous in circumstances with mixed traffic. The case for implementing road diets in some places is strengthened by the increased performance of AVs. The number of lanes and their width, for instance, could be decreased. In the long run, medians might be shortened or abolished since opposing-direction traffic may no longer require a safety buffer. The roadways of the future can be constructed very differently from the highways of today if vehicles are autonomous and on-street parking is not required. For AV-segregated infrastructure with proper communication infrastructure, clear signage, and lane marking, narrowing lane width is practical. When it comes to management, planning, and design, urban planners should consider looking for more effective and creative parking options.

CHAPTER I: INTRODUCTION

The objectives of this project are to: (1) conduct an information search from pertinent literature and and perform an assessment of Texas Road Design Standards under Automated Vehicle (AV) scenarios, (2) estimate the AV market penetration levels, (3) analyze the impact of AV on road capacity, (4) conceive innovative road design under AV scenarios, and (5) conceive innovative parking solutions under AV scenarios.

Since the emerging concept of autonomous vehicles (AV) and more importantly connected autonomous vehicles, there has been tremendous research focus on understanding the factors that influence their adoption. Analysis of market penetration is beneficial in creating economic forecasts that are relevant to auto industries and other supporting industries. It is anticipated that Connected and Automated Vehicle (CAV) market penetration will significantly impact such forecasts and outcomes. Also, understanding the market penetration of CAV will enable planners in making decisions for infrastructure needs for CAVs. The role of different behavioral theories along with the diffusion models in estimating the market share has been presented in various studies. Moreover, past research indicates that high trust in technology, a positive attitude towards AVs, and greater expected benefits may lead to increased chances of AV adoption. The impacts of certain attributes such as trust in technology, perceived benefits and concerns, and attitude on the adoption of AVs have also been analyzed in literature. The current road infrastructure is built for human drivers which is proving to be insufficient for AVs. At present, semi-autonomous vehicles are available in the market and they are equipped with various types of sensors, active safety systems, and driver-assist systems. AVs rely on visual detection and interpretation for movement. Hence, road markings and traffic signs play a vital role in the future of AVs. They must be developed and updated as per the requirements of AVs. For example, a study on road markings observed that 6-inch wide markings consistently outperformed 4 inch wide markings in numerous scenarios, especially under nighttime conditions. The road markings and traffic signs need to be maintained at a high standard in terms of cleanliness, clarity, deterioration, non-ambiguous positioning, and obscuration as the CAVs rely on visual detection and interpretation. Moreover, certain standardization regarding the markings and signages must be developed and followed by the various DOT's to assist the smooth operation of AVs. But solely relying on road signs and markings can backfire. Alternatives such as positioning the AVs with respect to the other vehicles, guard rails, and barriers, with input from several sensors and 3D maps must also be considered.

Approximately, 60% of a typical city is occupied by roadways networks right-of-way (ROW). This can be reduced by the introduction of AVs. The AVs can reduce the number and width of lanes, median requirements, and parking spaces thereby increasing open spaces that can be converted to bicycle lanes, green spaces, sidewalks, etc. The current standard width of a lane is kept at 12 feet to accommodate for human errors. With the use of AVs, lane width could be closer to the actual vehicle width, around 8 feet. In case of mixed traffic conditions, the standard width could be settled to 10 feet. Moreover, AVs will lead to shorter stopping sight distances and shorter length of vertical curves due to reduced reaction time, increased deceleration, and height of the sensor mounted on top of the vehicle. This will yield to economic and environmental benefits. There is however uncertainity regarding the safety and comfort of AVs in steep slopes. Moreover, the space required for the pick-up and drop-off points will increase. This will lead to a significant increase in the requirement and management of curb spaces.

Although AVs platooning may benefit road users with reduced congestion, improved fuel economy, etc., it can have detrimental effects on pavement stability. Hence, the optimal transverse location of trucks based on the platoon size has been discussed to minimize the damage. Further studies revealed that under low market penetration rates (10%), provision of priority lanes (HOVs along with AVs) were found to be beneficial when compared to exclusive lanes. Nevertheless, the throughput analysis showed benefits when lanes are reserved for AVs at a market penetration higher than 50% for the two-lane highway and 30% for the four-lane highway.

Parking is considered as one of the most land-intensive facilities and a substantial impediment to new development. Cities require parking space almost everywhere, and these parking lots, and large parking garages requirement are the critical links between the automobile and the urban form. Travelers sometimes are forced to pay large parking costs at their destination, especially if their destination is in the central business district. With the advent of AVs, parking will be largely uncoupled from other land uses. Unlike conventional vehicles, the AV can drop passengers off at almost any location, and then can park itself where parking fee is less. Parking might be shifted from the centers of high-value areas such as central business districts to lots in lower-cost peripheral areas. Additionally, AV can precisely park by themselves meaning smaller parking spaces will be required. Streets are expected to be narrower and curbside parking will disappear. Entire lanes or on-street parking can be easily reused for widened sidewalks, urban cycle tracks, open space, or even commercial uses like food trucks. In addition to reclaiming space from parking, the decoupling will facilitate creation of green spaces around shopping malls and urban activity centers as well as the historic preservation of older buildings. The focus of AV goes beyond vehicle design and technology and it has a major implication for the design and planning of inner cities. As AV begin to transform the way people get around, urban planners around the world are beginning to think about how this emerging disruptive technology will remake cities and change the way we live.

This technical report explains all the Tasks performed in the development of the Develop Roadway and Parking Design Criteria to Accommodate Automated and Autonomous Vehicles for the TxDOT. The report is organized as follows:

Chapter 1 presents an introductory of the topic and lists various chapters of the report.

Chapter 2 summarizes the available literature pertinent to various elements of road design such as lane width, sidewalks, highway weaving section spacing (ramp/auxiliary lane merge spacing), stopping sight distances for ramps and direct connections. The review reports of research focused on the connected autonomous vehicles (CAV) that has been performed in other states and abroad are presented that identify challenges related to road design elements and proposed solution related to automated vehicle future and their impact on road infrastructure and parking.

Chapter 3 reviews and recommends the changes to Texas road design standards.

Chapter 4 develops scenarios with varying market penetration level of automated vehicles.

Chapter 5 develops traffic performance measures to evaluate the efficiency of interrupted and uninterrupted road segments.

Chapter 6 studies the various innovative road design elements.

Chapter 7 studies the various innovative parking design elements.

Chapter 8 Provides conclusion and recommendations.

CHAPTER 2: LITERATURE REVIEW

TAXONOMY

The following definitions have been derived from the Society of Automotive Engineers (SAE) J3016 (*1*) and are helpful for understanding various levels of automation.

Dynamic Driving Task (DDT): Real-time tactical and operational functions that are required to operate a vehicle in on-road traffic as seen in Figure 1. This excludes trip scheduling and selection of destinations and waypoints and includes without limitations: lateral and longitudinal vehicle motion, object and event detection and response, maneuver planning, and enhancing conspicuity via lighting, and signaling, etc. (*1*, *2*).

Object and Event Detection and Response (OEDR): OEDR means monitoring the driving environment (detecting, recognizing, and classifying objects and events) and performing an appropriate response to such objects and events (*1*).

Operational Design Domain (ODD): SAE J3016 (*1*) defines ODD as “Operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics”. In simple words, ODD is the specific conditions under which a given automation system is designed to function and operate. As seen in Figure 2 once the ODD exits, the human driver is responsible for completing the remaining DDT. ODD is a system property and varies from system to system (*3*). For example, the sensors required to operate a vehicle on fully access-controlled freeways in low-speed traffic will be different from the sensors required for a shuttle operating at 10 miles per hour ferrying students inside the university.

DDT Fallback: It is the response by the vehicle or user either performing DDT or attaining minimum risk when a DDT performance related failure occurs or when ODD exit occurs.

Autonomous Driving System: Driving systems are termed autonomous if they can perform all the functions assigned to them independently and self-sufficiently. However, such driving systems have not been developed till now: even the most advanced driving system needs to communicate and exchange data with the outside entities and depend on algorithms and command of the remote user. The term autonomous driving is often used ambiguously and creates discrepancies. Some people associated autonomous driving with full driving automation (level 5); while others imply it to all automation levels (level 1 to level 5). Even some state legislation defines autonomous driving systems to correspond to ADS (level 3 and above) (1).

Automated Driving System (ADS): The driving system which can perform part or complete DDT (as per some pre-defined usage specifications) without the intervention of human drivers. In general, automated driving includes a set of specific tasks with pre-defined parameters. For example, an Automated Vehicle (AV) designed to operate exclusively within a university where it picks up and drops the students from their dormitory to their respective classes as specified by a remote user. The ADS is designed to perform specific functions repetitively and effectively (*4*).

Connected Driving System: This system of driving involves information exchange (communication) between the various AVs (themselves) and other non-AVs (V2V), infrastructure (V2I), cloud (V2C), and pedestrian (V2P) (*5*).

Cooperate Driving: Cooperate driving, as the name suggests, is the cooperation among vehicles and drivers within the traffic. The aim of such driving is to coordinate the microscopic objectives and actions of single traffic participants to improve the overall macroscopic effects (*6*). As per SAE J3216 (*7*), Cooperative Driving Automation (CDA) technologies can improve safety, mobility, efficiency, situational awareness, and reliability of the transportation system, which in turn can expedite the deployment of driving automation. CDA supports the movement of multiple vehicles in proximity to one another by sharing regular information that can influence the DDT performance.

Advanced Driver Assistance System (ADAS): ADAS are intelligent systems that reside inside a vehicle and assist drivers while driving and parking (*8*). These systems help the driver to perform easy tasks (e.g., cruise control) or difficult manoeuvers (e.g., overtaking and parking). ADAS can also assess the driving performance of the human driver and suggest some improvements. Some of the most common ADAS (*9*) are:

1. Adaptive cruise control,
2. Lane departure warning,
3. Lane keeping assistance,
4. Adaptive light control,
5. Automatic parking, and
6. Navigation system.

Cooperative Adaptive Cruise Control (CACC): CACC is the combination of sensors and vehicle-to-vehicle (V2V) communication which enables longitudinal AV control (enabling vehicles to adjust their speed as per the preceding vehicle in their lane) (*10*, *11*). The idea behind CACC is to have a shorter vehicle following distance, improve the traffic flow, and allow the vehicles to cooperate while in the CACC mode (*12*). Ultimately, this will lead to improved highway capacity and higher fuel efficiency.

Levels of Driving Automation

Level 1 -Driver Assistance: At this level, the vehicle can perform either the lateral or longitudinal motion control subtask of DDT but not both within the ODD, and the other dimension is performed by the driver. However, the vehicle cannot recognize or respond to few events hence driver is responsible for the OEDR subtask of DDT.

Level 2 - Partial Driving Automation: At this level, an ODD specific sustainable execution by the driving automation system which performs both lateral and longitudinal motion control tasks of DDT. In this scenario, the driver performs the tasks of OEDR and monitors the driving automation system.

Level 3 - Conditional Driving Automation: At this level, the ADS performs all tasks of the DDT within the ODD but the driver must take over the control of the vehicle when either ADS issues a request to intervene or DDT system-relevant failure occurs.

Level 4 - High Driving Automation: At this level, ADS is responsible for the tasks within the ODD and can perform DDT fall back without expecting the user intervention. This ability of the vehicle to come to minimum risk conditions on its own in case of emergency is the main difference between level 3 and level 4.

Level 5 - Full Driving Automation: At this level, the vehicle can perform all the operations unconditionally (i.e not dependent on ODD). In other words, a level 5 vehicle can drive under driver manageable conditions on its own. However, under adverse situations such as storms, floods, the vehicle performs DDT fall back and attain a minimum risk condition.

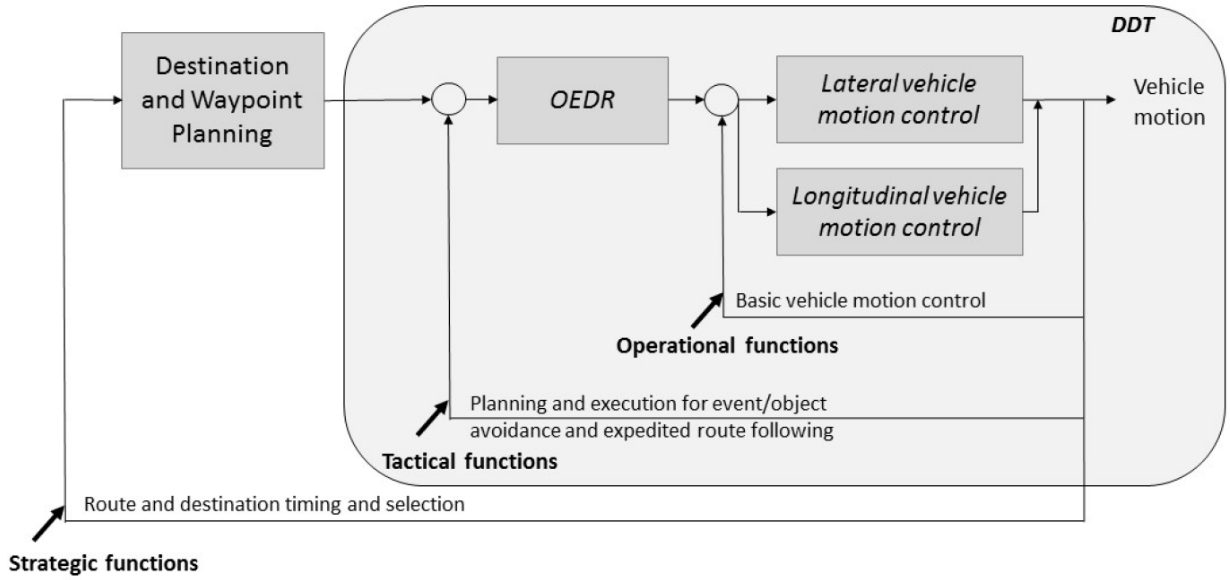


Figure 1 Schematic view of driving task showing DDT portion

Source: SAE J3016 (*1*)

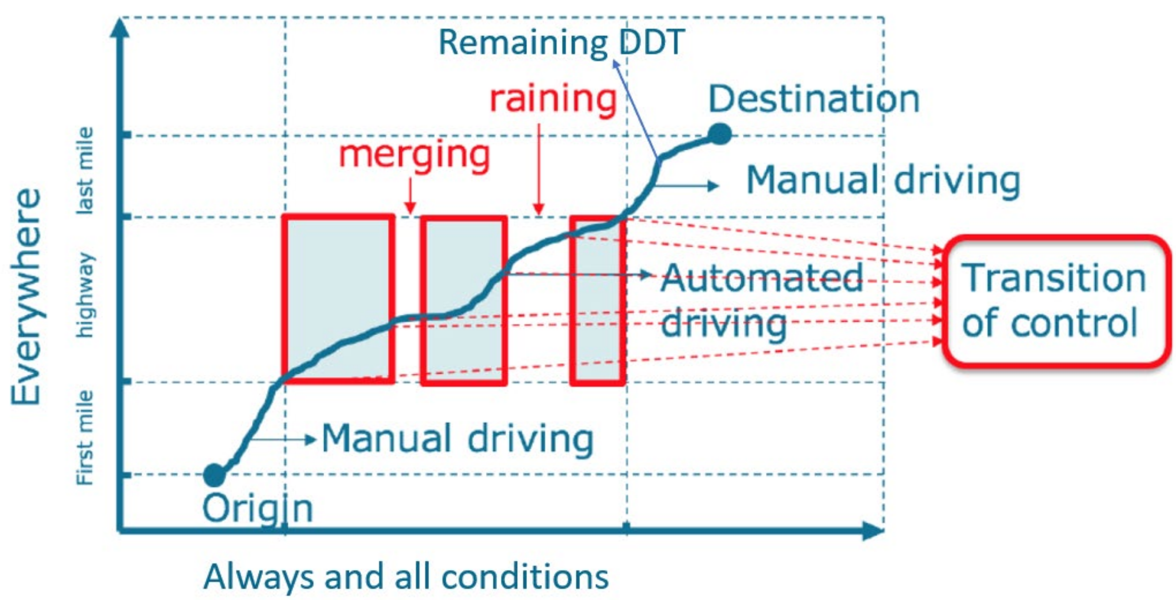


Figure 2 DDT handover to the manual driver once ODD exits. Source: Alkim (*13*)

In the literature, despite having different functional meanings, various researchers have used the terms automated, autonomous, and connected vehicle (CV) technology synonymously. Some of them have used the term autonomous vehicle to refer to a fully AV (level 5), while others have used it as a generic reference to the automation system. This study, however, is focused on driving automation level 3 and level 4.

ODD Scenarios

One of the first attempts at defining a standardized way of specifying the ODD has been BSI PAS 1883 and SAE AVSC Lexicon (*14*). The material came into effect on 31st August 2020 and was sponsored by the Centre for Connected and Autonomous Vehicles. Its development was facilitated by the BSI Standards Limited and was published under license from the British Standards Institution. Inspired by the work carried out by PEGASUS project, Germany (*15*, *16*), NHTSA, University of Waterloo and WMG's role in Streetwise Project, UK (*17*) and OmniCAV project, UK (*18*). BSI PAS 1883 (*19*) specifies a taxonomy for ODD attributes and has three high-level attributes:

A. Scenery: non-movable elements of the operating environment
B. Environment: weather and other atmospheric conditions
C. Dynamic elements: all movable objects and actors in the operating environment

Further categories and subcategories of the high-level ODD attributes as per PAS1883:2020 are presented in table 1.

Table 1 Top-level attributes ODD and their further classifications

High-Level ODD Attri-butes	General Attributes	Sub-attribute	Sub-attribute classification
Scenery	Zones	Geo-fenced areas	
		Traffic management zones	
		School zones	
		Regions or states	
		Interference zones, e.g., dense foliage or loss of positioning signal due to tall buildings	
	Drivable area	Drivable area type	a) motorways; b) radial roads; c) distributor roads; d) minor roads; e) slip roads; f) parking; g) shared space

		Drivable area geometry	a) horizontal plane; straight lines and curves b) transverse plane; divided/ undivided/ pavements/barriers on edges/ types of lanes together c) longitudinal plane: up-slope (positive gradient)/down-slope (negative-gradient)/ level plane
		Drivable area lane specification	a) lane dimensions; b) lane marking; c) lane type; d) number of lanes; e) direction of travel
		Drivable area signs	a) information signs; b) regulatory signs; c) warning signs.
		Drivable area edge	a) line markers; b) shoulder (paved or gravel); c) shoulder (grass); d) solid barriers (e.g., grating, rails, curb, cones); e) temporary line markers; f) none
		Drivable area surface	a) drivable area surface type; loose/ segmented/ uniform b) drivable area surface features; cracks, potholes, ruts, or swells c) drivable area induced road surface conditions: icy/ flooded roadways/ mirage/ snow on drivable area/ standing water/ wet road/ surface contamination
	Junctions	Roundabouts	a) signalized; b) non-signalized or, a) normal; b) compact; c) double; d) large; e) mini.
		Intersection	a) T-junctions; b) staggered; c) Y-junction; d) crossroads; e) grade separated

	Special structures	a) automatic access control b) bridges c) pedestrian crossings d) rail crossings e) tunnels f) toll plaza	
	Fixed road structures	a) buildings b) streetlights c) street furniture (e.g., bollards) d) vegetation	
	Tempo-rary road structures	a) construction site detours b) refuse collection c) road works d) road signage	
Environmental conditions	Weather	Wind	
		Rainfall	
		Particulates (obscuration by non-precipitating water droplets and other particulates	a) marine (coastal areas only); b) non-precipitating water droplets or ice crystals (i.e., mist/fog); c) sand and dust; d) smoke and pollution; e) volcanic ash
		Snowfall	
		Illumination	a) day b) night or low-ambient lighting condition
		Connectivity	a) communication: vehicle to vehicle communication (V2V)/ vehicle to infrastructure communication (V2I) b) positioning: Galileo/ Global Navigation Satellite System (GLONASS)/ Global Positioning System (GPS) V2X (which includes V2V and V2I): cellular, e.g., 2G, 2.5G, 3G, 4G, 5G/ satellite/ 802.11p-based WiFi, e.g., dedicated short-range communications (DSRC); intelligent transport systems (ITS-G5)

Dynamic elements	Traffic	Density of agents	Traffic shall include parked/stationary vehicles. Traffic agent type shall include vulnerable road users and animals
		Volume of traffic	
		Flow rate	
		Agent type	
		Presence of special vehicles (e.g., ambulance or police vehicle)	
	Subject vehicle	The subject vehicle's speed shall be an additional ODD attribute	

Source :PAS 1883:2020 (*19*)

Case Study: Connected and Autonomous POD on-Road Implementation (CAPRI): Capri pods (as shown in figure 3) are currently transporting members of the public around the Queen Elizabeth Olympic Park with visitors able to test out an innovative mobility service. Visitors can book a ride using an app through information marshals located at different stops along the pods' route (*19*, *20*). The ODD definition for this shared mobility pod system is as follows:

- Drivable area
  - Drivable area type: **shared space**
- Drivable area geometry
  - Horizontal plane: **straight lines, curves**
  - Vertical plane: **up-slope, down-slope, level plane**
- Drivable area surface
  - Drivable area surface conditions: **mirage, snow, standing water, wet road**
  - Drivable area surface features: **cracks, swells**
  - Road surface type: **segmented, uniform**
- Environmental
  - Wind: **up to 15 m/s**
  - Rainfall: **up to 10 mm/h**
  - Snowfall: **light snow, moderate snow**
  - Illumination: **day, night, cloudiness, artificial illumination**
- Dynamic elements:
  - Agent types: **vulnerable road users, animals, non-motorized agents**

Figure 3 Connected and Autonomous POD on-Road Implementation (CAPRI). Source: CAPRI

CONSUMER ACCEPTANCE OF AVs

Ever since the concept of AV and more importantly CAV garnered recognition there has been tremendous research that has been conducted in understanding the factors that influence their adoption. Analysis of market penetration is beneficial in creating economic forecasts that are relevant to auto industries and other supporting industries. It is anticipated that CAV market penetration will significantly impact such forecasts and outcomes. In addition, understanding the market penetration of CAV will enable planners in making decisions for infrastructure needs for CAVs. Various efforts have been put by researchers in investigating the different aspects of the adoption. Even though the approaches are diverse, the goal was to understand the AVs and CAV's acceptance. Further behavioral theories such as the theory of planned behavior, technology acceptance model, and diffusion of Innovation theory have been employed to discern consumer acceptance.

Behavioral Theories

The *Theory of Diffusion of Innovation*, developed by Rogers (*21*), investigated the potential to adopt any innovative product based on the concept of *relative advantage, compatibility, and complexity*. First, the concept of *relative advantage* determines the edge a new technology/product has over the existing technology/product that is going to be replaced. Then the second concept namely, *compatibility* is used to measure the degree to which the new technology is aligned with an individual need. The greater the compatibility higher is the likelihood of adoption. The third concept *complexity* measures the efforts required in adopting the new technology. In other words, it is the measure of the degree of ease with which the idea/technology can be implemented. Further, Rogers categorized the consumers into five groups or categories. These groups are *innovators, early adopters, early majority, late majority, and laggards*. *Innovators* although very low in percentage are the ones who influence early adopters. *Early adopters* are the group where the majority of opinion leaders are present. The early adopter group is the most significant in scaling up an innovation. This is because most of the consumers in the system are not equipped with the recent information and hence tend to follow the leaders (predominantly present in the early adopter's group). Hence as per Rogers, this group is the most critical group which can rapidly diffuse the product into the market and have the potential to make it an essential commodity in an individual's day to day life. Therefore, unsurprisingly, understanding the preferences of the early adopter group has been the target of existing literature.

Another category of behavioral theories that are predominantly present in the existing literature is based on the *Theory of Planned Behavior* (TPB) developed by Ajzen (*22*). Based on the behavioral beliefs, this theory aims to explain the behavioral intention of a consumer rather than predicting the actual buying behavior. As shown in Figure 4, the TPB is mainly based on three beliefs: behavioral belief, normative belief, and control belief. These beliefs are measured using three components namely, attitude, subjective norms, and perceived behavioral control respectively. However, the framework is flexible enough and it can be tailored based on the objectives of the study. Hence numerous researchers have proposed an extended TPB to study different aspects of AV/CAV adoption.

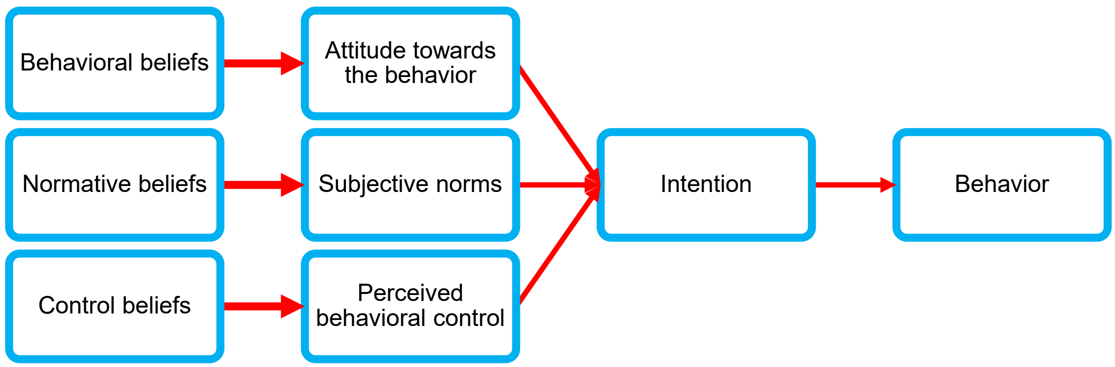


Figure 4 Theory of Planned Behavior

Technology acceptance model (TAM) is another model in this domain that is similar to the TPB that was originally developed to determine the acceptance of new technologies (*23*), (*24*). As shown in Figure 5, it was found by Panagiotopoulos & Dimitrakopoulos (*24*), that TAM consists of two beliefs: *perceived usefulness* and *perceived ease to use*. First, perceived usefulness measures the degree to which the new technology will enhance the performance. Then the perceived ease of use measures the complexity involved in using the new technology. Later it was found by Venkatesh & Davis (*25*) that both of these factors had a direct significance on the behavioral intention thereby characterizing the attitude construct (*26*).

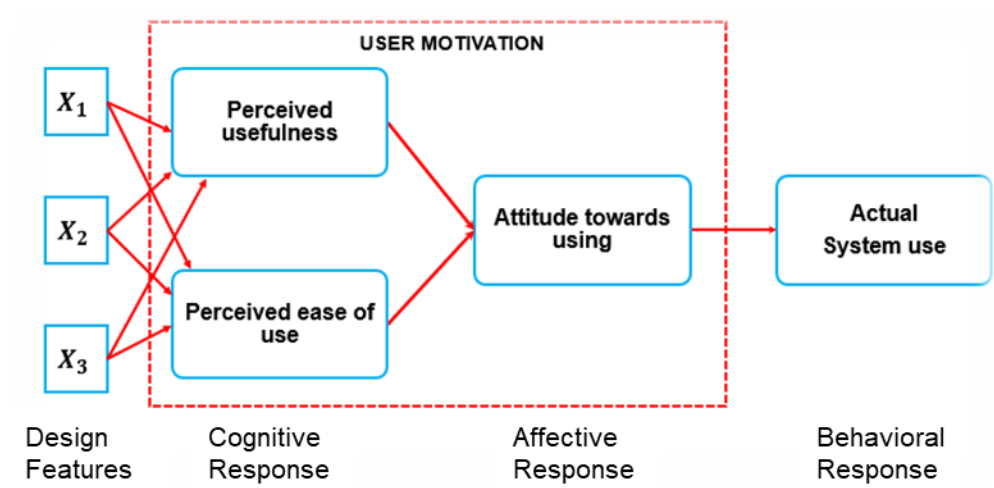


Figure 5 Technology acceptance model framework

Global Perspective of AVs

A study performed by Schoettle & Sivak (*26*) attempted to understand the acceptance of AVs in multiple countries including China, Japan, United Kingdom, US, India, and Japan. They observed that most of the people showed positive evaluations of the benefits of AVs and had a high initial positive opinion. Especially the responses from China and India showed more positive evaluation than other countries whereas the responses from Japan were neutral towards AVs. Even though the initial opinions varied over different countries, the majority of them had concerns about the safety of AVs. These concerns were found to rise when the AVs are fully autonomous (i.e., Level 4 and above) without driver controls. Similar kind of study was performed in Finland, by Liljamo et al. (*27*) that focused extensively on identifying the factors and concerns in adopting an AV. Based on the responses of around 2000 people they observed that the people who expressed a positive opinion on AVs belong to the early adopters group. Among them, most of them were found to be men, highly educated, and were living in a house without a vehicle. However, the concerns remained similar to that concluded in the study by Schoettle & Sivak (*26*) with many respondents expressing their anxiety over the traffic safety of AVs. Another concern of the Finnish people was the fear of incomplete trips or interrupted trips because of the unreliability of technology.

Haboucha et al. (*28*), using stated preference survey, examined around 721 individuals in Israel and North America. They observed that the early adopters of AV are more likely to be young, highly educated and individuals who generally spend most of their time in vehicles (*27*). Moreover, in Israel men are likely to adopt the AVs faster than women. Moreover, the factors that can influence the decision choice making for these individuals were concern towards environment and enjoyable driving. Liu et al.(*29*) found that social trust and perceived benefits are significant factors in explaining the acceptance of AVs.

Attitude of the consumer was found to be one of the most critical components in explaining the acceptance of AVs and CAVs. Hence numerous studies have incorporated the attitude of consumers in determining the AVs adoption. Nielsen & Haustein (*30*) categorized the group of respondents from Denmark into three categories based on the attitudes towards the conventional vehicles and AVs as *Sceptics, Indifferent stressed drivers, and Enthusiasts*. They found that these groups of people significantly differ in their socio-economic profiles. *Enthusiasts* were generally young males who are highly educated and live in large urban areas. *Sceptics* on the other hand were older and more often located in sparsely populated areas. *Indifferent group* was those who are least interested in vehicles and are generally last individuals in adopting them. In similar lines, Payre et al. (*31*) included contextual acceptability and interest in impaired driving along with attitudes in predicting the acceptance of AVs in France. The contextual acceptability was measured in terms of safety, drivers' control, boring and passengers in the vehicle whereas the impaired driving measures whether the drivers were under influence of drugs or alcohol and experienced fatigue. It was further concluded that the inclusion of contextual ability described some unexplained part due to attitude. Moreover, around 71% of the respondents of the study were favorable towards fully automated driving while being impaired.

König & Neumayr (*32*) focused on knowing the significant barriers towards the AVs adoption and he observed that less familiarity with technology could lead to a more cautious approach of adopting an AV. Moreover, most of the people were concerned about the safety of the system, especially from hackers. Further few people expressed that handing over control to the machine may imply becoming dependent and losing driving skills (*33*). Further, it was observed by Fraedrich & Lenz (*34*) that most of the people who are concerned with AVs rely on the mass media for information on AVs. Moreover, it was noticed that the information from mass media is authoritative whereas the information from social media is bidirectional (*35*). Hence, recognizing the importance of media Zhu et al. (*36*) researched the role of media on the adoption of AVs. They developed a media-based perception and adoption model in examining the role of social and mass media. This model investigated the impact of media on the human's perception especially on self and on the product in the city of Beijing.

Another class of AVs that have been largely gaining importance is the shared autonomous vehicles (SAVs). Krueger et al. (*37*) found that people viewed SAVs on two dimensions with dynamic ride sharing and without dynamic ride sharing. They further identified that travel attributes such as travel cost, travel time, and waiting time are crucial in adopting SAVs. Young cohorts and individuals who are accustomed to multimodal travel are more willing to use SAVs.

United States Perspective

Trust in AVs

Abraham et al. (*38*) observed that for people to adopt an AV trust is the foremost thing. Further, it is of utmost importance to recognize that trust is developed over a period of time and can be abraded quickly with few negative incidents. These results were consistent with the findings of Kaur & Rampersad (*39*) in Adelaide who observed that there was a lack of public trust especially due to privacy and security concerns. Howard (*40*) also observed that gaining trust in the technology is very difficult since it is new and unproven. These results were in line with the findings of Schoettle & Sivak (*26*) who observed that the US consumers had a less favorable evaluation of the AVs and were concerned with safety, system performance in adverse weather conditions, and data privacy. However, it is important to note that to have sufficient confidence in the technology people must have sufficient awareness of the technology. Bansal et al. (*41*) observed that most of the city of Austin residents were Tech-savvy with around 92% possessing a smartphone and about 80% have heard about Googles AVs. These results were encouraging especially from the Texas perspective because as noticed by Sanbonmatsu et al. (*42*), generally least knowledgeable consumers are those who have less favorable opinions towards AVs.

Perceived Benefits or Concerns of AVs

Bansal et al. (*41*) measured the perceived concerns or benefits in adopting an AV and observed that majority of the people believed AVs can reduce the number of crashes, decrease traffic congestion and improve fuel economy. However major concerns were possibilities of system failures, legal liability of drivers, the privacy of people, and affordability of vehicles. Howard (*40*) made a similar kind of observations with the results suggesting that AVs can mitigate environmental issues, improve fuel economy through truck platooning, and decrease the congestion in a road network. Moreover, it was also believed that AVs could improve the equity issues and with the introduction of SAVs, a greater number of people can access the transport network efficiently. Further, the size of land required for urban parking can also be minimized achieving a more sustainable solution. However, even though the benefits are substantial the cost involved in achieving them is significantly high especially in procuring sensors etc. The high initial cost and low confidence in the product can make the adoption much more challenging.

In addition to the benefits observed by Bansal et al. (*41*) and Howard (*40*), Schoettle & Sivak (*26*) observed that after the introduction of CAVs, the emergency response of crashes could be reduced considerably. Further, the travel time of trips can get shorter, and the insurance premiums can become lesser. Moreover, it was noted that AVs can eliminate crashes due to the distracted driving phenomenon. Furthermore, there were concerns about the system and vehicle security. Interestingly it was found that with the introduction of AVs people were anxious that drivers will have to rely heavily on technology. Underwood (*43*) observed that legal liability and providing regulations for AVs were ranked as the most difficult barriers to overcome since the technology of AVs is at such a novel stage. Shariff et al. (*44*) observed that people might overreact in case of inevitable incidents and such incidents can prove to be detrimental in encouraging the AVs adoption. Shabanpour et al. (*45*) identified that with the introduction of AVs the trouble of finding parking may diminish and the driving may become more enjoyable and stress-free leading to productive use of travel time. Nevertheless, even though there were enough benefits of AVs, people were equally concerned about few aspects of AVs for example AVs can cause an unfriendly environment for bicyclists and non-AV drivers. Furthermore, people were not sure how AVs perform in an unexpected situation and liability in case of an accident. Casley et al. (*46*) also had similar findings in their study, the majority of the respondents were not in a position to take liability for an incident when they are not driving. However, this could be resolved when further laws are brought into place and people are educated on the same. Efficiency and environmental impact are the driving factors of AV adoption whereas productivity did not have much encouraging influence on AV adoption. Sharma & Mishra (*47*) reported that the benefits provided by AVs and CAVs to disabled people were outweighed by their concerns towards AVs. For instance, the CAVs may fail when there is poor communication infrastructure requiring individuals to take the control of AVs.

Attitudinal Factors

Analyzing an individual's personality has been a long-term practice in developing a fair understanding of the individual's behavior. In general, data such as socio-economic, demographic data, travel data, etc. are collected and are associated with behavioral characteristics. This association is particularly important because there is sufficient evidence in the literature to say that human behavior is almost similar within each cohort. This section discusses the results of few studies related to attitudinal characteristics in the adoption of AVs.

Asgari & Jin (*48*) measured the attitude of drivers under four latent constructs: the *joy of driving, trust on passengers, technology savviness, and mode choice reasoning*. It was observed that people who loved their driving were very hard to convince towards vehicle automation whereas people who are tech-savvy showed the highest interest in vehicle automation. Interestingly people who believed the current ride-sourcing to be insecure believed that vehicle automation can bring more privacy to their trips. Moreover, people were prepared to pay if the AVs provide better utility in terms of travel time, cost, stress, etc. Hardman et al. (*49*) also made similar kinds of observations for instance on technological environmentalists, frustrated commuters, driving enthusiasts etc. Further, it was found by Spurlock et al (*50*) that the adoption rate among risk lovers was almost 13% higher than those who had risk-neutral preferences.

Tussyadiah et al. (*51*) measured the attitude of people to investigate the role of AVs and commuting trips. In this study, the attitude was measured in terms of trust on AVs and perception of technology. High trust in AVs and low negative evaluation of technology encouraged the AVs adoption. Further, it was found that people preferred AVs for tourism rather than the daily commute. Rahimi et al. (*52*) investigated the generation gaps between millennials and generation X on AVs. Millennials were favorable towards on-demand trips, transit trips and have higher technology acceptance when compared to generation X. As a result, it was found that there is a substantial attitude gap that must be considered while projecting for the AV demand services. Sener et al. (*53*) observed the social influence on the purchase intention of AVs and it was found to have a positive relationship with the adoption behavior. Moreover, Sharma & Mishra (*47*) observed that possessing a CAV improves the social value among peers.

Willingness to Pay (WTP) and Market Penetration

Schoettle & Sivak (*26*) calculated the WTP for various countries. Results showed that people from China showed the highest WTP for Level 4 automation. The 75th percentile was around $8000 for the people of China whereas the people of the US were willing to pay only $2000. Moreover, around 54.5% of the people in the US were not willing to pay an additional for vehicle automation. Asgari & Jin (*48*) performed a descriptive analysis to identify the additional WTP for different levels of automation. Eventually, the WTP for partial automation ranged around $1,542 and $1,769 for full automation.

A study by Kockelman et al. (*54*) on the WTP for different AV levels and connectivity of consumers at the US level and Texas level, revealed that with the existing NHTSA's regulations around 98% of the US fleet will have connectivity between years 2025 to 2030. Assuming constant change in WTP and technological price reduction annually along with assumed regulations eight scenarios have been assumed in this study as described in Table 2. It was found that under most optimistic conditions (scenario 8) the adoption rate for Level 4 raises as high as 87.2% by the year 2045 whereas with constant WTP and no regulations in place the adoption percentage is the least at 24.8% as observed in Figure 6.

Table 2 WTP increase, tech-pricing reduction, and regulation scenarios

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

Source: Kockelman et al. (*54*)

Further, the report findings indicated that approximately 54.4, 31.7 and 26.6% of Texans were not willing to pay more than $1,500 for Level 2, Level 3, and Level 4, respectively. On Average, a Texan is willing to pay around $2,910, $4,607, $7,589, and $127 for Level 2, Level 3, Level 4, and connectivity, respectively. It was found that around 47% of them are planning to go for an AV based on their peer's adoption rates. On average a Texan is willing to spend $6.8 to save 15 minutes in a 30-minute one-way trip, this finding highlights the importance of time for an average Texan who is willing to pay significantly to reduce travel time.

Bansal et al. (*41*) studied the WTP among city of Austin residents. It was recognized that the average WTP for level 4 automation was around $7,253 which was significantly higher than the average WTP for level 3 ($3300). However, these results are contradicted by Daziano et al. (*55*) and it was found that an average household WTP is $3,500 for partial automation and $4,900 for full level automation. The difference in the results was attributed to the differences in survey methodology.

Lavasani et al. (*56*) developed a generalized bass diffusion model based on a combination of conventional and hybrid electric vehicle (EV) sales data with the usage of internet on cell phones. The analysis suggested that if the AV sales start in the year 2025 around 8 million vehicles will be sold by the year 2035 and saturation will occur by the year 2060 assuming market share of 75%. However, Talebian & Mishra (*57*) observed that aggregate diffusion models such as bass models cannot accommodate the dynamic nature of individual perceptions. Hence for this purpose, a disaggregate agent-based simulation model was proposed and it was observed that for AVs to exist homogeneously in the market by the year 2050 there must be a substantial drop in prices annually (for example 15 to 20%). The proposed price drops of 5% annually in the previous studies appeared to have less than significant impact with the Connected AVs reaching only 15% of all vehicles by the year 2050. Moreover, it was noticed that a pre-introduction marketing campaign for 6 months may not have any significant impact on the adoption trends.

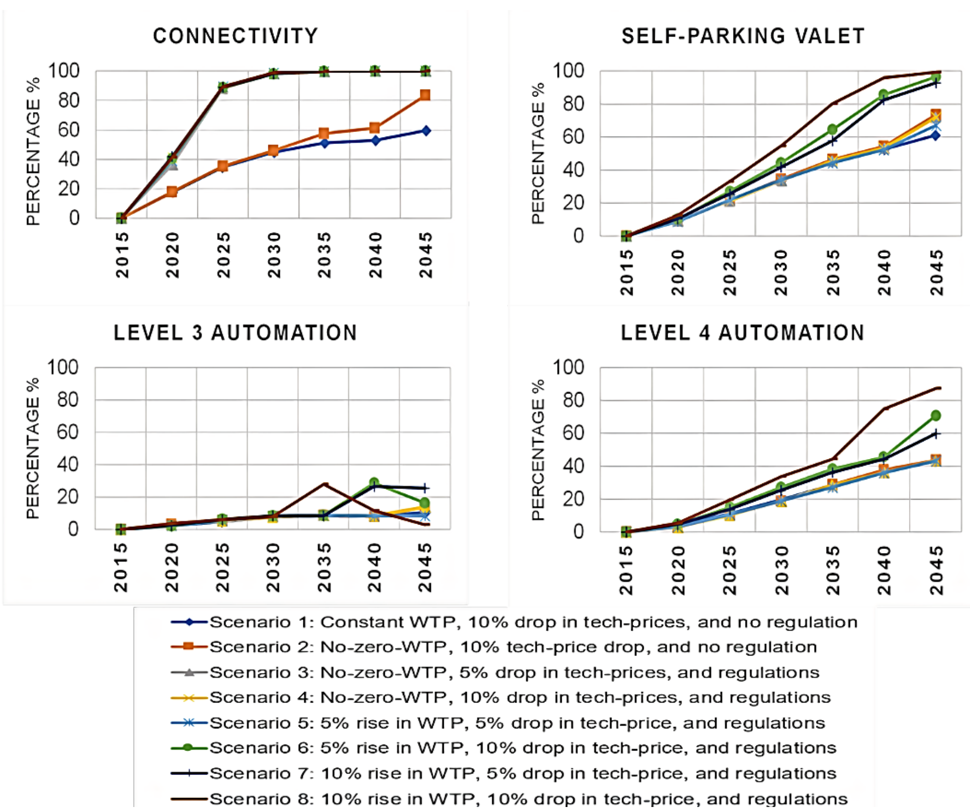


Figure 6 Estimated shares of U.S. light-duty vehicles with advanced automation. Source: Kockelman et al. (*54*)

However, in contrast to the Talebian & Mishra (*57*), Nieuwenhuijsen et al. (*58*) used an aggregated system dynamics modeling to understand the diffusion of AVs in the market. This study assumed three scenarios: base scenario (No subsidies and external funds), AV in bloom-conservative (here attributes are better than base scenario but not as beneficial as AV in bloom-progressive scenario), AV in bloom-progressive scenario (Most optimistic scenarios). It was determined that if AVs had started rolling out in the year 2000 then around 86% of the vehicles would have been level 5 automated and 59% by the year 2050, under AV in bloom-conservative and AV in bloom-progressive scenario, respectively.

In addition to the above discussed diffusion models, there are other diffusion techniques applied to predict AV growth. For example, Chen et al. (*59*) used the modified logistic growth model proposed by Yang & Meng (*60*) in predicting the AVs diffusion. According to this model, the AV diffusion in a year depends on the AV adoption in a given year and net benefits gained in the previous year. This study focused on identifying the impacts of having a dedicated AV lane on market penetration. It was found that market penetration reaches the saturation point after 26 years irrespective of the market size. Moreover, the AV market penetration was found to be insensitive to the lane capacities of AV.

IMPLICATION OF AVs ON ROADWAY DESIGN

Above 90% of road accidents are caused due to human errors. More than 2,400 lives could be saved on Texas roadways in a year, with more than $14 billion in economic savings when the market penetration of AVs reaches above 90% (*61*). Moreover, once the AVs become prevalent, the roadways ROW can be recaptured (as AVs travel closer and, in a platoon, with tighter vehicle tracking and space for parking requirement is reduced). Similarly, the width standards of lanes, shoulders, clear zones, and medians can be reduced due to the lane-keeping system followed by AVs (*62*, *63*). This will result in the availability of free space which can be converted into an additional lane (lane dedicated to platoons), curb extension, dedicated bike lane, open green spaces, etc.

Lane Markings

The importance of lane markings in driving a semi-autonomous vehicle was visibly highlighted when Volvo's semi-autonomous prototype refused to drive when it failed to identify the lane markings (*64*). In contrast to the US, other developed countries have greater standardized road marking and signage making it less difficult for AV to traverse. Hence to negate the transportation infrastructure, automakers suggest additional sensors to make the vehicle more effective. However, such incorporation of sensors calls for an additional cost. Boston consulting group estimated that the inclusion of basic semi-autonomous features increases the cost of a vehicle by $4000 (*64*).

A recent study by Pike et al. (*65*) on pavement markings addressed many of the concerns addressed above. Their study focused on recognizing the importance of pavement markings in ADAS such as Lane Departure Warning (LDW) and Lane-Keeping Assistance (LKA). Generally, the LDW and LKA are achieved using machine vision captured through sensors and cameras mounted to the vehicle. Hence their study concentrated on evaluating the impacts of four-inch wide and six-inch wide pavement markings on the detectability of machine vision. For this purpose, eight preformed pavement marking tapes under varying levels of retro-reflectivity and color was developed. Further, the performance of these markings was tested in six combinations of radiance and environmental conditions: daytime dry, daytime wet, nighttime dry, nighttime dry with glare, nighttime wet, and nighttime wet with a glare. Results showed that 6-inch wide markings performed better than 4-inch wide markings in most scenarios. Under dry conditions, during both daytime and nighttime, with a good state of repair conditions performed similarly. However, under wet conditions, the 6-inch wide lane marking performed better than that of 4-inch marking in terms of detectability. Further, during daytime, the detectability of machine vision was greatly decreased with an increase in speeds. However, in contrast under nighttime conditions, the detectability either improved or remained the same with increased speed (*66*).Further solid markings were easily detectable in comparison to the broken markings. Moreover, to account for the situations where there was not enough distinction between pavement surface and lane markings their study tested a contrast marking (4-inch wide marking paralleled with 2-inch wide black striping on each side). Mixed results were obtained for contrast markings with the largest benefits observed during daytime and negative effects being detected during nighttime. Based on the findings, the study ranked the marking characteristics in the following order: presence of pavement markings, contrast ratio, pavement markings width, wet weather characteristics, line pattern, and texture of markings. Moreover, the faults in lane support systems can be predicted using the luminance coefficient of markings and horizontal curvature radius (*67*).

Adaptive Cruise Control

A microsimulation study has been performed to recognize the benefits of the Co-operative Adaptive Cruise Control (CACC) (*68*). It was determined that with the Adaptive Cruise Control (ACC) drivers did not have sufficient confidence to maintain close gaps between the vehicles. In contrast with CACC, drivers were able to select closer gaps. Further, the results of the study identified that as the proportion of CACC increased from 0 to 100% the lane capacity increased from 2000 VPH to 4000 VPH. CACC benefits have relied upon the market penetration rate, time headway, and vehicle-following model. An efficient CACC may result in reduced time headway and following distance. For conventional vehicles the headway is around 1.4s, but for an efficient CACC, the platoon headway can be as low as 0.6s (*69*).

Road Infrastructures and Traffic Control Devices (Road Marking and Traffic Signals)

Kockelman et al. (*61*, *70*) studied the traffic impacts of autonomous vehicles and concluded that AVs can increase the lane capacity, intersection capacity, passenger flow, and reduce the fleet sizes. Several road infrastructures need to be developed to accommodate the successful development and implementation of intelligent driving technologies. Table 3 presents the various infrastructure needs and costs, as per the automation levels and technologies (as per NHTSA, 2013 (*71*)), alongwith the potential need for TxDOT involvement. Out of the different automation levels, level 3 and level 4 technologies face the most significant barriers and uncertainties in terms of: high cost, security and privacy, and operation in the transition stage.

Liu et al. (*72*), in their study, suggested a three-phase road infrastructure upgrade plan (see Table 4): maintenance phase, segregated-infrastructure expansion phase, and application of simplified standard phase. The status of each stakeholder (manufacture, road users, and the government) was also considered while developing the upgrade plan. Their research found that there is need to upgrade the current traffic signs and road markings, roadworks communications, digital communications, pavement structure, road surface, parking, and service stations following the three defined phases. Moreover, a cost-benefit analysis was performed, and their results validate the upgrade process. It is to be noted that their study was carried out by extensive literature review and largely depends on the immature CAV market.

Table 3 Infrastructure needs evaluation for various technologies

S.N.	Technology	Automation Level	Infrastructure Need	Infrastructure Cost	TxDOT Involvement
1	Forward Collision Warning	Level 0: No Automation	None	None	Infrastructure
2	Blind Spot Monitoring		None	None	Policy
3	Lane Departure Warning		Lane marks	Low	Infrastructure
4	Traffic Sign Recognition		Traffic sign	Moderate	Infrastructure
5	Left Turn Assist		Lane marks	Low	Policy
6	Adaptive Headlight		None	None	Policy
7	Adaptive Cruise Control	Level 1: Function Specific Automation	None, possible dedicated lane	Depends	Policy
8	Cooperative Adaptive Cruise Control		None	None	Policy
9	Automatic Emergency Braking		None	None	Policy
10	Lane Keeping		Lane marks	Low	Infrastructure
11	Electric Stability Control		None	None	Policy
12	Parental Control		None	None	Policy
13	Traffic Jam Assist	Level 2: Combined Function Automation	Lane marks	Low	Policy
14	High Speed Automation		Lane marks, traffic sign	Moderate	Policy
15	Automated Assistance in Roadwork and Congestion		Lane marks, beacons, guide walls	Relatively high	Policy
16	On-Highway Platooning	Level 3: Semi-Automation	Lane marks, traffic sign	Moderate	Policy
17	Automated Operation for Military		None	Unknown	Policy
18	Driverless vehicle	Level 4: Full Automation	Lane marks, traffic sign, lighting	Relatively high	Both
19	Emergency Stopping Assistance		None	None	Policy
20	Auto-Valet Parking		Parking facilities	Relatively High	Both

Source: Kockelman et al. (*61*, *70*)

Table 4. The three-phase upgrade plan

No	Start time	CAVs %	Automation level	Manufacture (techniques) status	Road users (market) status	Govt. policy status	Upgrade standard
1	Now	<20%	Level 0	Mature	Dominant	Release CAVs testing standards	Mainte-nance
			Level 1-2	Prove to be efficiency	Early adopter		
			Level 3-4	Prove to be reliable	Turn-out		
			Level 5	Testing	Rarely seen		
2	2030s	20-50%	Level 0	Mature	Gradually eliminate	Road ROW division	Segreg-ation
			Level 1-2	Mature	Dominant		
			Level 3-4	Prove to be efficiency	Faithful adopter		
			Level 5	Prove to be reliable	Turn-out		
3	2050s	>50%	Level 0	Mature	Nearly disappear	Ownership change; Energy substitution	Simplifi-cation
			Level 1-2	Mature	Gradually eliminate		
			Level 3-4	Mature	Dominant		
			Level 5	Prove to be efficient	Faithful adopter		

Source: Liu et al. (*72*)

The road markings and traffic signs need to be maintained at a high standard in terms of cleanliness, clarity, deterioration, non-ambiguous positioning, and obscuration as the CAVs rely on visual detection and interpretation (*73*). Johnson (*74*) studied the readiness of the current infrastructure and found the inadequacy of the traffic signals as well as the road markings and signages. There are already documented examples in the USA of trial CAVs coming to a halt due to substandard road markings (*74*). Moreover, the current lack of standardization on signals and signs within states, let alone across states, is likely to cause a significant hindrance to the ability of CAVs (*75*). Therefore, coordination between the various DOT's regarding consistent road markings and signages are needed throughout the USA. Furthermore, regardless of the level of automation of vehicles, the road should be sufficiently equipped with clear road markings and adequate traffic signs to accommodate AVs and CAVs.

However, solely relying on lane markings to control automated driving is not a wise strategy. It is unrealistic to think that all roads will have lane marking in good condition all the time. So, despite most of the literature suggesting improving lane markings, we must also look at various other alternatives to assist AVs. Different V2V and V2I communication alternatives such as positioning the AVs with respect to the other vehicles, guard rails, and barriers, with input from several sensors and 3D maps must also be considered (*76*). Many partially and fully AVs under development typically use machine vision systems such as radars and cameras to identify road markings (*76*). For the short term, improving and maintaining road markings could be beneficial to attract early adopters. However, it is not beneficial in the long run. Since AV technologies are always evolving there is no fixed infrastructure to support V2I applications. As per GAO (*77*), the infrastructures needed to support V2I communication includes both the road infrastructure and user-related (vehicle) equipment as shown in Figure 7.

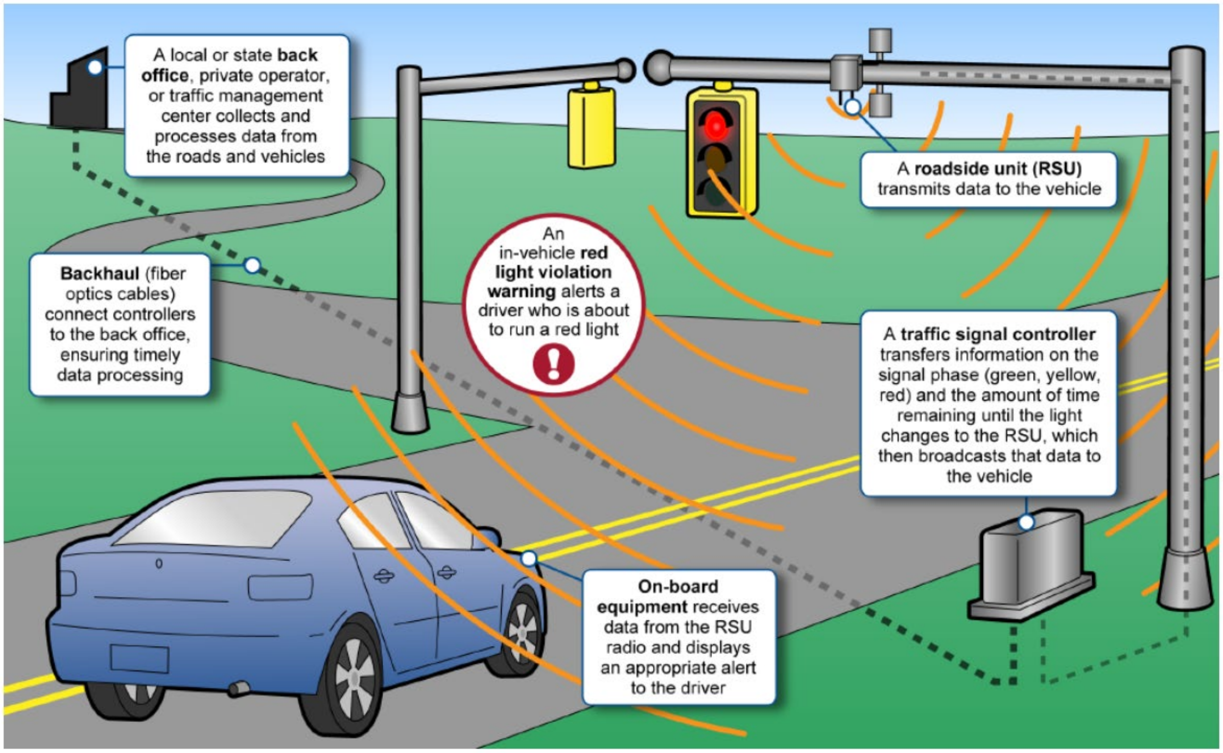


Figure 7 An example of V2I application and roadside equipment

Source: GAO (*77*)

Road Design Elements (lane width, shoulder widths, curb modifications, SSD, and length of vertical curves)

Approximately 60% of a typical city is occupied by road ROW (*78*). Riggs et al. (*78*) in their poetic language emphasize that rather than expanding and widening roadways and promoting VMT and collision among vehicles, we should re-prioritize the use of valuable street real state to promote collision among people by increasing the sidewalks, open green spaces and parks facilitating social interactions. Improved performance of CAVs will make a strong case for developing road diets in some areas (*77*). For example, CAV will travel with a shorter headway, thereby increasing the traffic capacity and reducing the number and width of lanes. Moreover, in the long run, the median between two opposing traffic directions may not be needed and could be narrowed or even removed.

The current standard width of a driving lane is kept at 12 feet to accommodate for human errors. When AVs is deployed, lane width could be closer to the actual vehicle width (*76*). This will result in a reduction of the lane width by about 20%— for a width of about 8 feet. In case of mixed traffic conditions (conventional vehicle and AVs), the standard width could be set to 10 feet.

This will benefit conventional vehicles, pedestrians, and bicyclists by demoting risky driving behavior and lowering vehicle speed, thus promoting safety (*79*).

Concepts of bi-directional lanes are also emerging. This will reduce the total lane width required and lead to a pedestrian-friendly-side-streets. Due to the V2V and V2I capabilities of AVs, they could interact with each other, and the infrastructures present around them to coordinate movements. These concepts can easily be implemented on some residential streets and areas with low traffic volumes (*80*). However, to maximize the potential benefits, such as improved traffic capacity, reduced congestion, and reduced lane widths will require the majority of all the vehicles on a road to operate autonomously (*81*).

Currently, level 2 and under certain limited operational domains level 3 AVs are available in the market. In the case of a semi-autonomous vehicle (level 2), automation capabilities are limited, and the system occasionally fails while perceiving the road path, transferring the control to the human driver. García & Camacho-Torregrosa (*82*) established a framework to test lane width-related disengagements without considering the vehicle technology of a semi-autonomous vehicle (level 2 as per SAE J3016 (*1*)). An ODD threshold of 2.50m to 2.75m was defined: that is whenever the width of the road decreased below 2.50m, the human-driven had to take control of the steering. Conversely, whenever the width of the road was over 2.75m, the automated system performed as intended. Their study is limited to a single lane keeping assist (LKA) system and was conducted during daylight and good weather conditions. However, the result of the study can be used as a component while defining ODDs and determining the width-related disengagements along a corridor.

On one hand, AVs can reduce the parking space required. On the other, the space required for pick-up and drop-off points needs to be increased. This will lead to a noteworthy increase in the requirement and management of curb space. This problem will be significant in high-density neighborhoods (for example there will be a huge demand when thousands of employees of a multi-storied building want to get home after completing their work all at the same time but in different directions). Therefore, urban areas will need to price curb space, and prioritize them for public AVs, shared AVs, and for people with disabilities (*80*).

A study done by Riggs et al. (*78*) proposed a zonal approach for urban and suburban streets, where the road users were prioritized by speed and use intensity. The excess space made available due to switching to AVs can be converted into sidewalks, bike lanes, and public transit as shown in Figure 8. However, this zonal approach is only feasible when the market is saturated with AVs. It is straightforward to have narrow road width containing wider curbs, more cycle space, and tighter corner radii for a newly constructed road; but for an existing road, narrowing it may lead to the problematic outcome for non-AV traffic (*74*).

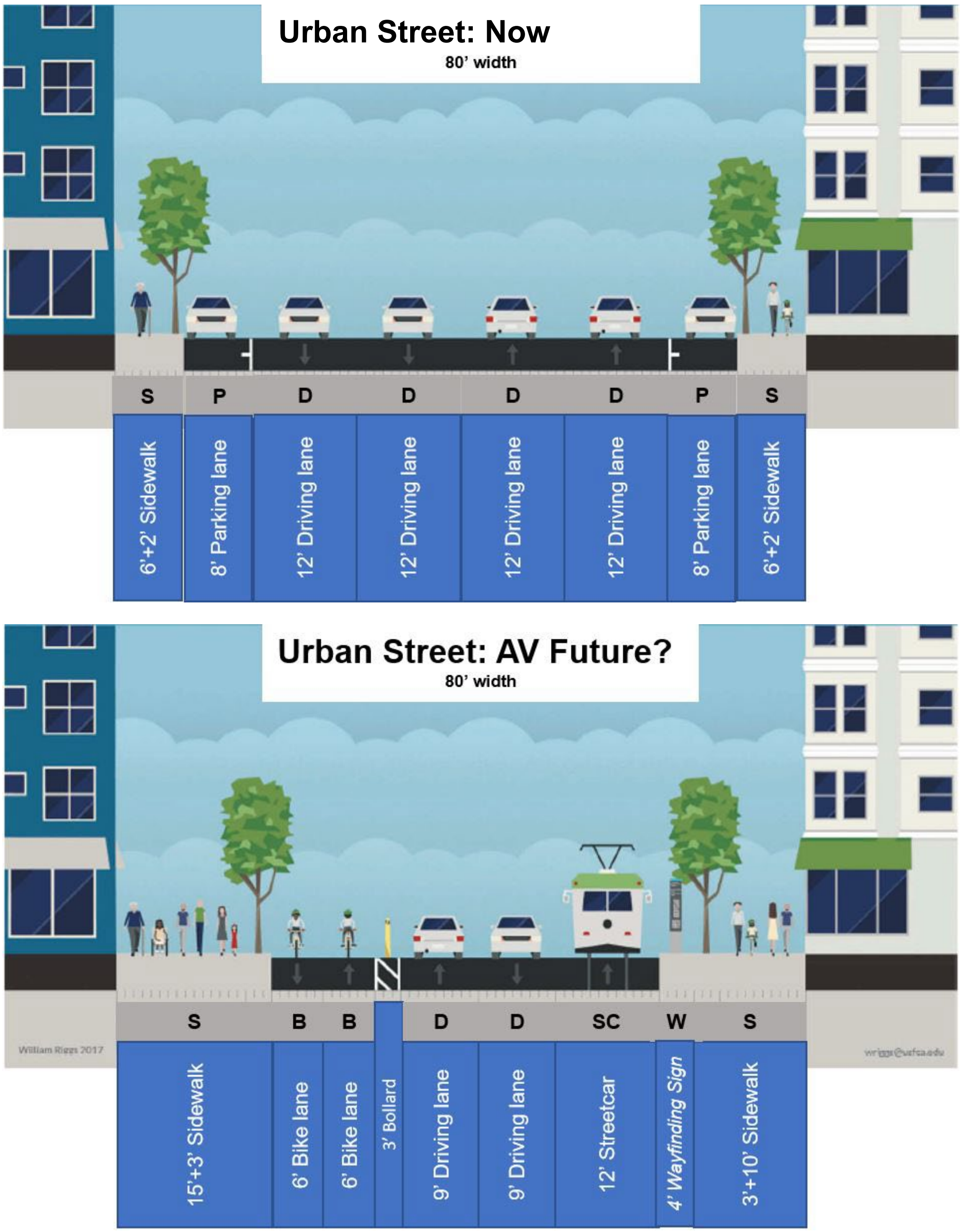


Figure 8 An evolution of an urban street section in an era of AVs. Source: Riggs et al. (*78*)

A researcher using design tool ReStreet developed various hypothetical scenarios on a four-lane urban arterial road(as observed in Figure 9) and estimated the amount of savings in ROW (*83*). He considered that for a lane width of 8 feet AVs can navigate easily and conventional vehicles could move at a slower speed. In these circumstances, he estimated the following savings in

ROW as given in (Table 5). He further emphasized these savings on land can be utilized for improved movement of people for instance development of bike lanes, sidewalks, transit lanes, etc. or can be reserved for future purposes.

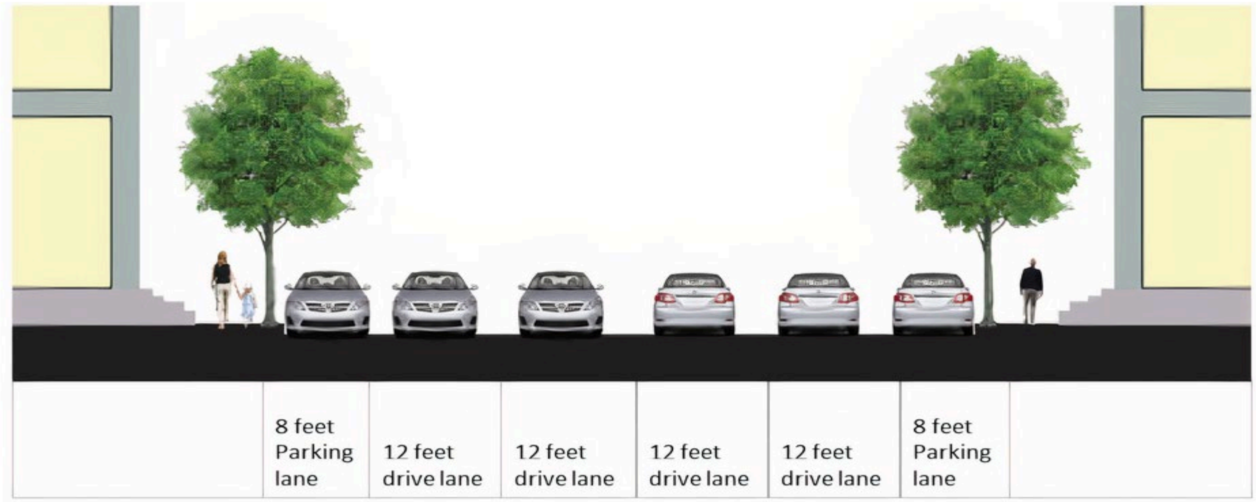


Figure 9 Four lane urban arterial section

Source: Schlossberg et al(*83*)

Table 5 ROW savings under different scenarios

No.	Scenario	Description	Right of way (ft)	Percentage saved with respect to the base scenario
1	Base scenario (existing condition)	Four-lanes with parking lanes on either side	48 + 16 = 64	0%
2	Thin lanes (8ft each)	Four lanes with parking lanes on either side	32 +16 = 48	25%
3	Removal of one parking lane	Four lanes with parking lanes on a single side	32 + 8 =40	37.5%
4	Removal of either parking lanes	Four lanes arterial with no parking lanes	32	50%
5	Share travel lane	Three lanes including a shared middle lane (Vehicles in either direction can access it)	24	62.5%

Source: Schlossberg et al(*83*)

An interesting observation was that the AVs could reduce the freeway lane width by 25% saving the cost of construction materials by at least 33% (*84*). However, another study inferred that even with the reductions in lane width and decreased headways, the capacity improvement is not as drastic as reported in a few of the earlier studies (*85*). Further simulations were performed on two-lane and three-lane segments to determine the percentage increase in freeway capacity. The amount of increase under various market penetration rates (MPR) with different base capacity are given in tables 6 and 7.

Table 6 Capacity of two lanes under various MPR of AVs

Two-Lane	Base capacity (pc/hr/ln)		
MPR (%)	2400	2100	1800
0	1.00	1.00	1.00
20	1.02	1.03	1.14
40	1.07	1.10	1.27
60	1.13	1.26	1.43
80	1.22	1.37	1.63
100	1.34	1.52	1.82

Source: Kittelson (*85*)

Table 7 Capacity of three lanes under various MPR of AVs

Three-Lane	Base capacity (pc/hr/ln)		
MPR (%)	2400	2100	1800
0	1.00	1.00	1.00
20	1.01	1.01	1.15
40	1.07	1.10	1.26
60	1.12	1.23	1.37
80	1.21	1.36	1.56
100	1.36	1.54	1.82

Source: Kittelson (*85*)

As observed in tables 6 and 7, for a lane having capacity of 2400 pc/hr/ln, which is an ideal condition, the capacity improves by 34-36% for an MPR of 100%. Although an interesting finding from the study was that the regular lanes do not generally operate under ideal conditions due to various reasons such as missing shoulders, human distraction, etc. These factors were eliminated with AVs and roads having an initial base capacity of 1800 pc/hr/ln can accommodate close to 3300 pc/hr/ln with the same ROW.

There is a lack of literature regarding the shoulder requirement for AVs. As per the taxonomy classification of AVs by the SAE (*1*), the ADS equipped vehicles (level 3 to level 5) may encounter occasional DDT fallback. In such cases, the ADS will try to achieve minimal risk conditions. So, the use of the shoulder will be imperative in conditions when the ADS- equipped vehicles must step aside (due to DDT- fallback) of the main lane to prevent the hindrance to the traffic flow.

The current technology cannot be used to determine the significant changes to roadway design standards based on the difference between sight distance among human observers and machines (*86*). But the time taken by AVs to respond to the obstacles (apply the brakes) once they are detected will likely be quicker than that of conventional vehicles. This will lead to a significant increase in the design speed of roadways provided that all other factors remain the same. The current roads and highways are designed as per the human drivers. This may not be efficient for AVs. The current roadways must be updated to meet the design standards for AVs (*87*, *88*). Khoury et al. (*87*) studied the geometric design elements that will be directly impacted when the road is occupied by a fully autonomous vehicle fleet such as stopping sight distance (SSD), decision sight distance, length of crest vertical curve, and length of sag vertical curve. In their study, the perception reaction time of the driver was changed from 2.5 sec to 0.5 sec (also see (*89*)); the height of the driver's eye above the roadway (1.08 m) was replaced by the height of the lidar sensor mounted on top of the SMART vehicle (1.7 m); the height of headlight over road surface is replaced by the height of sensor (1.7 m); inclined angle of headlight beam was changed from 1° to 13.4°. The results obtained from modified values were compared with the standard AASHTO value, and significant reductions in SSD, DSD, and length of vertical curves were obtained. Moreover, the proposed model was also implemented to check its validity in a real-world road section. The already constructed road as per AASHTO's design guidelines was virtually reconstructed using Civil3D and the difference between cut and fill volumes were compared. A schematic view of one of the sections showing the visual difference between the current and proposed design is given in Figure 11. The result showed that the cut volume decreased by 7.67% and the fill volume decreased by 47.22%. However, this will lead to a steeper slope (as shown by Figure 10) which in turn will question the operation and movement of AVs regarding safety and comfort criteria.

Similar research was conducted by Welde and Qiao (*88*). This study was divided into three scenarios. The first scenario was the base case where the current design standards given by AASHTO were used. The second scenario considered the deployment of level 3 AVs in presence of a human driver. And the last scenario considered fully AVs without any human driver. For scenario 2, a reaction time of 0.5 sec (*87*, *89*) was taken whereas, for scenario 3, the reaction time was further reduced to 0.2 sec without providing any sort of reference or computation. Moreover, the deceleration rate for scenarios 2 and 3 was changed from 3.4 m/sec^2 to 4.5 m/sec^2 (*90*). The height of the driver's eye above the road surface was taken as 1.838 m. In their study, however, the headlight height and the inclined angle of the headlight beam were taken the same as that of AASHTO's guidelines. Hence, only the effect of changing SSD was observed while calculating the length of the sag vertical curve. The study concluded with a suggestion for significant reduction in the SSD, and length of vertical curves for the latter two scenarios. Besides the above-mentioned literature, few works have been done in the field of geometric design for AVs. The major research works relevant to AVs and CAVs are being done in the field of digital infrastructure rather than the physical infrastructure (*62*). Hence, there is a need for research focus towards the effect of AVs on the physical infrastructures relevant to road design.

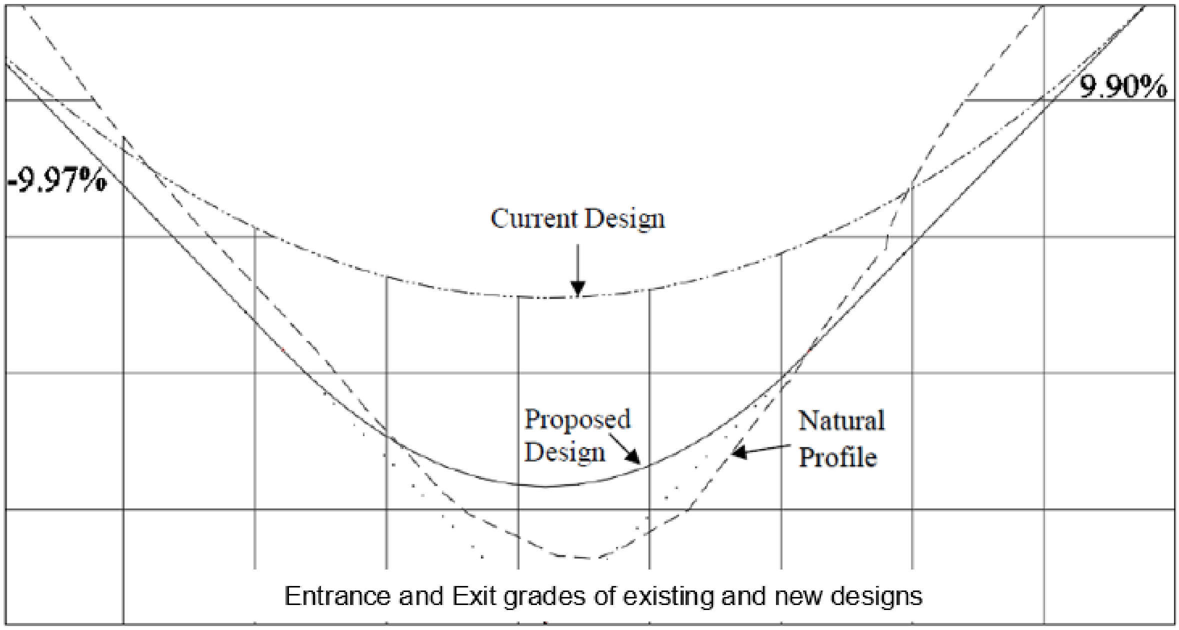
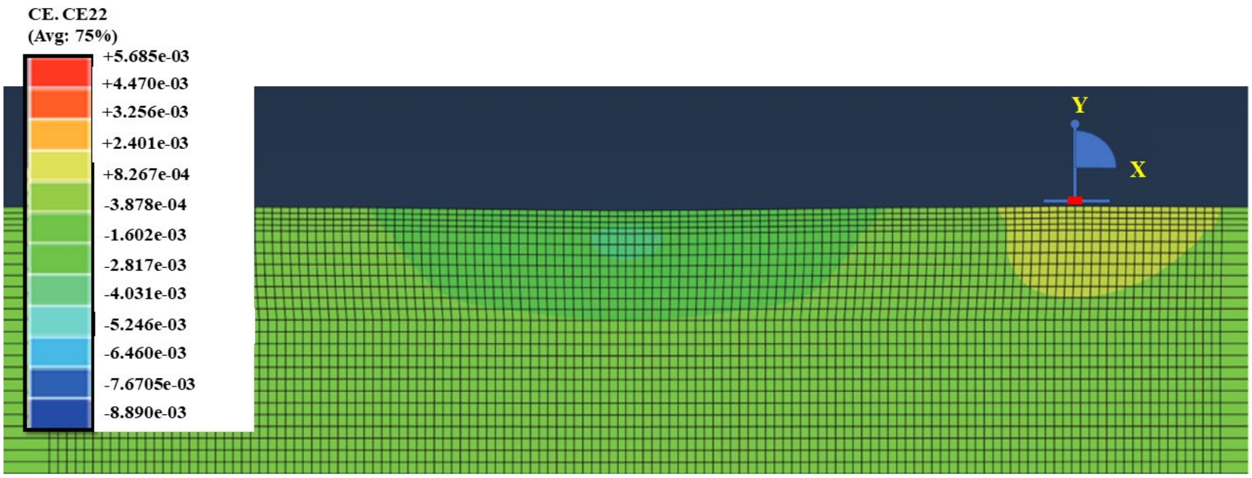


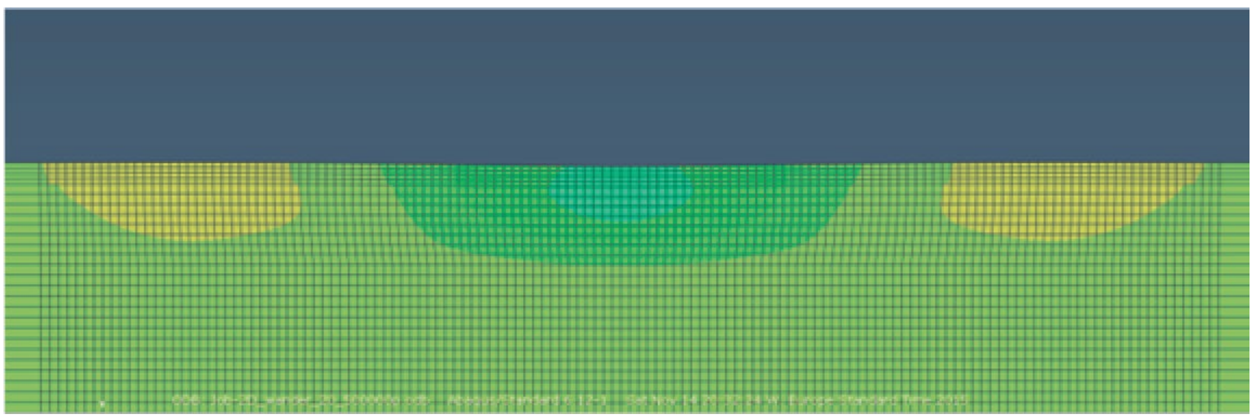
Figure 10 Schematic view of the difference between the profiles of current design (AASHTO) and proposed design. Source: Khoury et al. (*87*)

Platooning of Vehicles

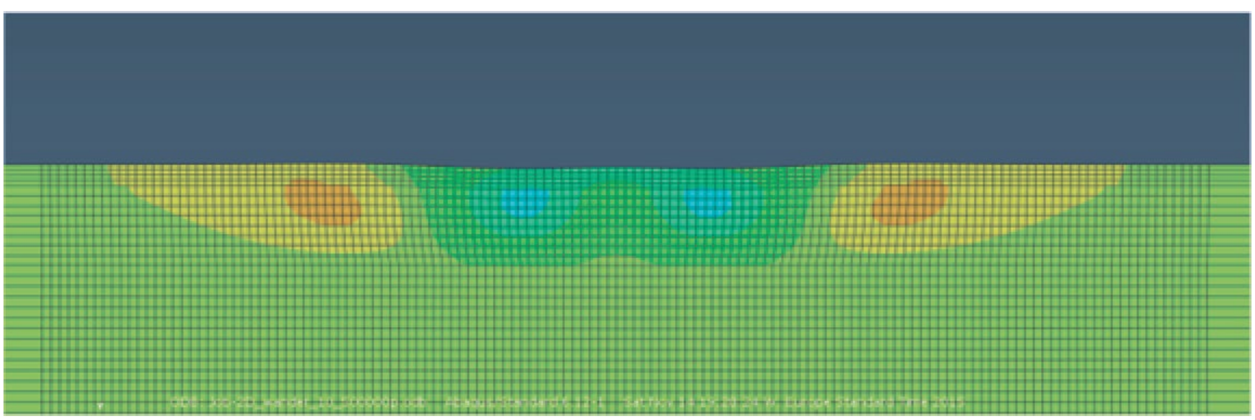
Platooning of vehicles produces a reduced time gap and thereby increases the lane capacity. Moreover, along with associated benefits such as reduced congestion, improved fuel economy, etc. platooning of AVs can have detrimental effects on pavement stability. To understand these effects a study using KENPAVE software examined pavement rutting performance for different wheel wanders conditions (*91*). To be specific, four-wheel wander conditions for AVs, 0.20 m, 0.10 m,0.05 m, and zero were compared with 0.26 m for conventional vehicles. After allowing for 5.0 * 10^5 passes for heavy vehicles with a speed of 100 kph the pavement rutting was calculated for the above conditions. The simulated results of accumulated creep strain distribution were observed as given in Figure 11. The study result shows that maximum rut depth increased from 0.43 mm at wheel wander of 0.26 m to 1.19 mm at zero wander. Further as given in Figure 12 the rut depth decreased by about 50% with an increase in speed from 10 to 50 km/h.



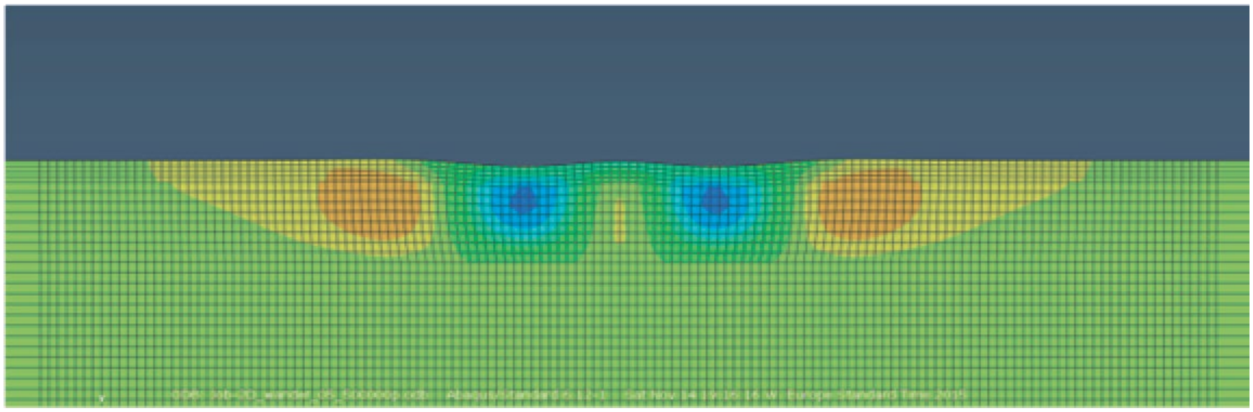
(a) Wander_0.26 m, maximum rut depth = 0.43 mm



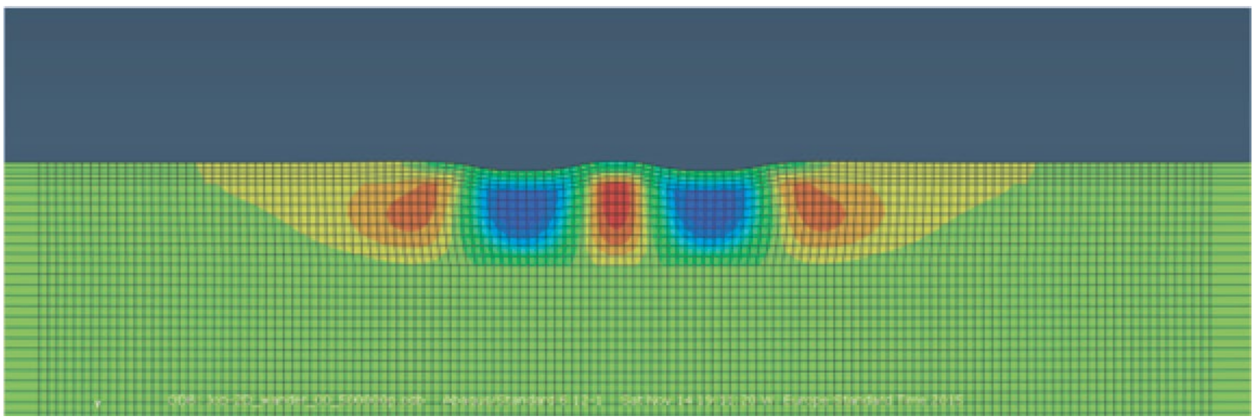
(b) Wander_0.20 m, maximum rut depth = 0.48 mm



(c) Wander_0.10 m, maximum rut depth = 0.62 mm



(d) Wander_0.05 m, maximum rut depth = 0.92 mm



(e) Wander_0 m, maximum rut depth = 1.19 mm

Figure 11 Profiles of deformed pavement structure (with scale factor of 10) and distributions of accumulated creep strain by level of wheel wander

Source: Chen et. al (*91*)

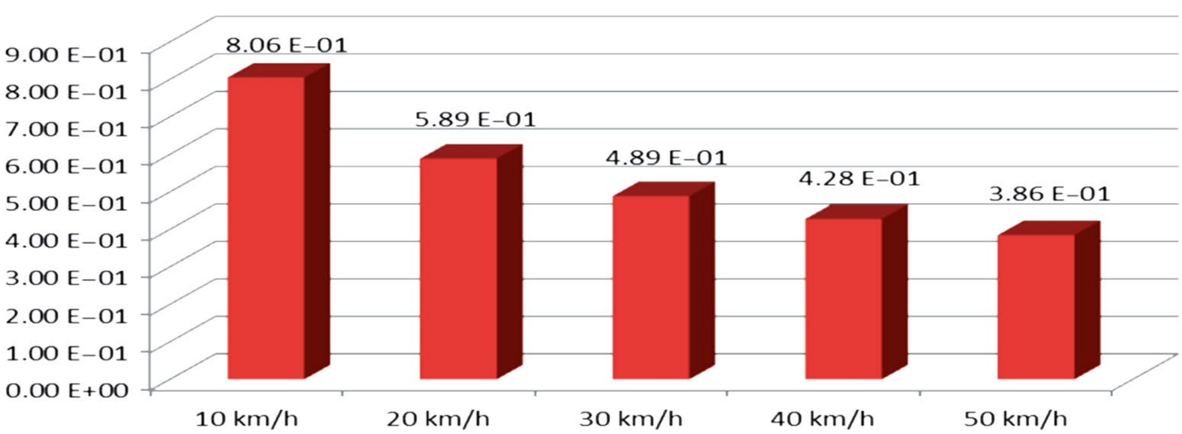


Figure 12 Maximum rut depths by level of traffic speed. Source: Chen et. al (*91*)

Moreover, it was observed by another researcher that the equivalency factors for autonomous trucks with zero wander are 2.1 to 2.3 for rutting and around 1.15 to 1.27 for fatigue (*92*). An optimization algorithm was used by a group of researchers in identifying the optimal lateral position of autonomous trucks (ACT) to minimize the extent of damage on the pavement (*93*). Various platoon sizes ranging from 2 ACT to 10 ACT were studied in their research. The transverse distance of ACT under each platoon size (represented by p) along with their inter-vehicle distance (in centimeters, represented as "Sep") is given in Table 8.

Table 8 Optimum skeletons for varying platoon sizes

# of trucks	P1 (cm)	P2 (cm)	P3 (cm)	P4 (cm)	P5 (cm)	P6 (cm)	P7 (cm)	P8 (cm)	P9 (cm)	P10 (cm)	Sep. (cm)
2	336	356									396
3	332	347	360								383
4	349	360	340	328							418
5	240	259	267	275	293						401
6	346	328	309	293	274	255					339
7	355	338	320	302	284	266	249				326
8	243	247	266	275	303	326	334	345			327
9	240	256	264	279	294	316	332	347	352		312
10	360	351	345	332	321	293	273	263	259	246	325

Source: Gungor O.E. et al. (*93*)

The optimal locations for platoon size of 10 vehicles are graphically represented as given in Figure 13. Moreover under 100% penetration of ACT it was observed that for a period of 45 years there was a reduction of about 9% in the total costs (sum of agency costs and user costs in $M) when compared to base scenario (no lateral shift). The net gain for each platoon size when compared to the base scenario is presented in Table 9.

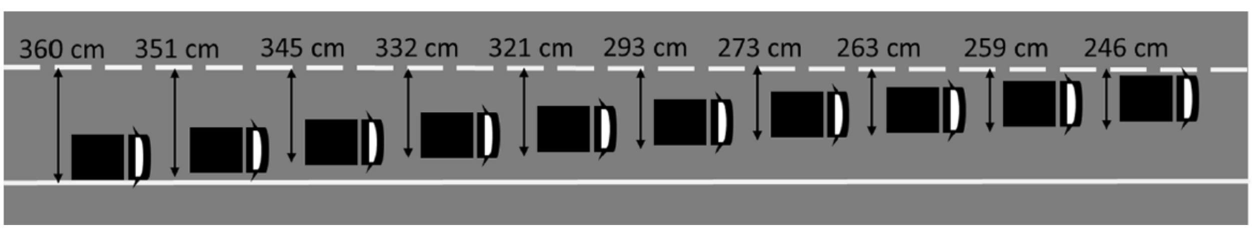


Figure 13 Optimum skeleton for the platoon with 10 trucks. Source : Gungor, O.E.et.al (*93*)

Table 9 Optimization results for varying platoon sizes

# of Trucks	Base Case ($M/Km)			Optimal case ($M/Km)			Net Gain ($M/Km)		
	Agency cost	User cost	Total Cost	Agency cost	User cost	Total Cost	Agency cost	User cost	Total Cost
2	0.94	4.27	5.21	0.5	4.41	4.91	0.44	-0.14	0.3
3	0.94	4.07	5.01	0.45	4.19	4.64	0.49	-0.12	0.37
4	0.94	3.9	4.84	0.4	4.06	4.45	0.54	-0.16	0.38
5	0.94	3.79	4.73	0.4	3.94	4.34	0.54	-0.15	0.39
6	0.94	3.71	4.66	0.35	3.88	4.23	0.59	-0.16	0.43
7	0.94	3.66	4.6	0.33	3.82	4.16	0.61	-0.16	0.45
8	0.94	3.62	4.57	0.3	3.79	4.08	0.64	-0.16	0.48
9	0.94	3.59	4.54	0.3	3.73	4.02	0.64	-0.13	0.51
10	0.94	3.57	4.51	0.28	3.71	3.99	0.66	-0.14	0.52

Source: Gungor O.E. et al (*93*)

Dedicated Lanes for AVs and CAVs

Some past studies have shown that the maximum benefit of AVs on the optimization of highway capacity can only be obtained when the market penetration rate of AV is high (*94*, *95*). Talebpour et al. studied the effects of reserving a lane for AVs on congestion and travel time reliability to overcome this limitation (*96*). A state-of-the-art microscopic simulation framework (*97*), which utilizes a vehicle-following and lane-changing model, was used to model the acceleration and lane-changing decision of manual and AVs. The study was conducted in two different road sections: (a) a hypothetical two-lane highway with an on-ramp and (b) a four-lane highway segment on Interstate 290 near Chicago, IL. The results showed improvement in congestion, decrease in the scatter of fundamental diagram, and better travel time reliability when the AVs were given the choice to either use the reserved lane or stick with the regular lanes (optional use of the reserved lane), provided no limitations placed on the type of operation. Moreover, the throughput analysis showed benefits when lanes are reserved for AVs at a market penetration higher than 50% for the hypothetical two-lane highway and 30% for the four-lane highway. A similar study was conducted by Covas et al. (*98*), where exclusive lanes were designated for autonomous vehicle platoons, which showed a reduction in the average travel time for the city commuters of São Paulo.

Ye and Yamamoto (*99*) studied the impacts of CAV dedicated lanes on traffic flow throughput using a three-lane heterogeneous model flow. They found negative impacts on the overall throughput as indicated by the fundamental diagram during the low market penetration of CAVs. The negative impact decreased as the penetration of CAV increased. However, when the traffic flow was dominated by CAVs (high penetration of CAV), the benefit of dedicated CAV lanes decreased. The study also concluded that setting a higher speed limit in the CAV dedicated lanes than other normal lanes will enhance the performance of the dedicated lanes.

A National Cooperative Highway Research Program (NCHRP) research also studied the need for dedicating lanes for CAVs and AVs (*100*). As observed in Figure 14, the provision of the dedicated lane had an impact on three categories of stakeholders: dedicated lane users, general-purpose lane users, and facility owners. Further, the net benefits gained due to the provision of a dedicated lane are dependent on the factors such as CAV market penetration, roadway geometry, CAV technology, and functional types as described in Figure 14. Moreover, this NCHRP report also deals with various CAV applications such as CACC and Dynamic Speed Harmonization (DSH). The DSH recommends target speeds to the equipped vehicles based on congestion incidents and road conditions.

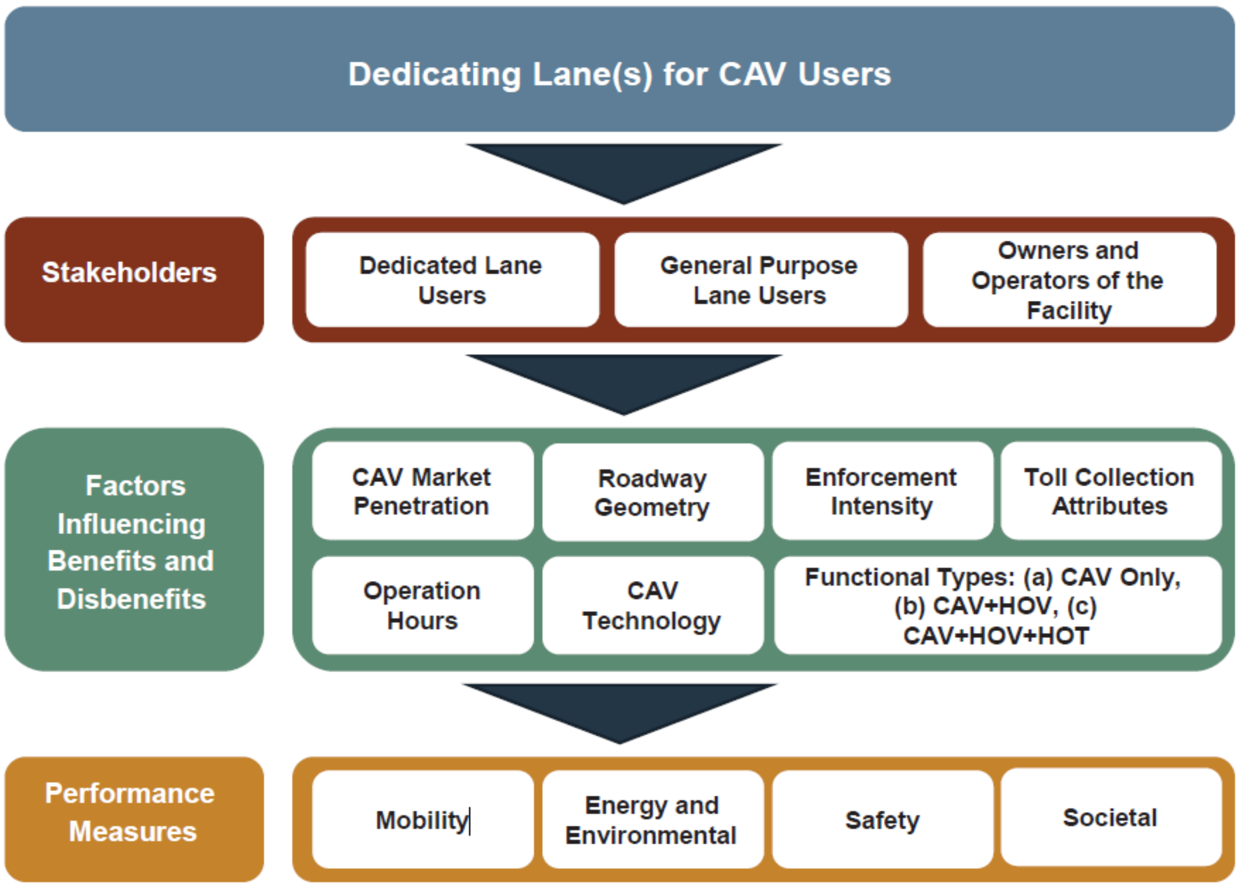


Figure 14 Benefit/drawbacks categories, influencing factors and affected stakeholders. Source: Hamilton et.al (*100*)

In the above stated NCHRP study (*100*), two case study sites I-66 from northern Virginia and the US-101 corridors in San Mateo were selected, and models were developed for these study sites. Using simulation modeling three dedicated lane scenarios were developed - base case (only high occupancy vehicles (HOVs) can travel on Dedicated lanes (DLs)), priority case - HOVs and CAVs can share DL, exclusive lane - CAVs only on DLs. The results of two scenarios – priority and exclusive lanes- are tabulated in table 10.

Table 10 Network performance under shared and exclusive DL use

Mobility performance measures	Shared with HOVs		Exclusive CAV DLs			
	10% CACC	10% DSH	10% CACC	10% DSH	25% CACC	25% DSH
Change in Travel time	1%	41%	92%	73%	-13%	13%
Change in average speed for general purpose lane	3%	-10%	-31%	-28%	0%	-11%
Change in average speed for dedicated lanes	6%	-37%	37%	-20%	36%	-16%
Change in overall fuel consumption	-1%	65%	83%	65%	-16%	21%
Lane friction (mph)	2	2	35	26	10	15

Source: Hamilton et.al (*100*)

As observed from table 10, at lower market penetration levels (10%) the incorporation of CACC was found to be beneficial for priority lanes when compared to exclusive lanes. Further, the CACC application enhanced network efficiency by increasing the throughput of DLs. However, DSH had contrasting effects, at higher market penetration levels, CACC reduced travel time by 13% but the average speeds increased significantly. Overall, it was observed that at lower market penetration levels sharing of lanes with HOVs was beneficial whereas for higher market penetration dedicating a lane to CAVs was beneficial to overall network mobility. In addition, the lane friction grew with the increase in market penetration thereby suggesting the need for physical segregation of DLs.

Weaving and Merging of AVs

As discussed in the taxonomy section, for autonomous driving, a single vehicle can make its own driving decision independently. For connected driving, information is exchanged between automated as well as non AVs and other traffic participants and/or infrastructure in an automated way. Cooperative driving means that single vehicles and drivers act cooperatively within traffic. Connected driving improves the abilities for cooperative driving, because traffic participants can express and share their intention more easily and precisely. Single traffic participants are coordinating their microscopic aims and actions in the light of improved overall macroscopic effects. This helps the other traffic participants for an improved consideration in their cooperative actions. Since the coordination with the help of connected driving is not only possible at microscopic level but also on macroscopic level, further potential for improvements in traffic efficiency and effectiveness are released. Cooperative and connected driving can lead to improved traffic even without automation. Cooperation is also possible without connectivity in the case the (automated) traffic participants strictly follow given rules and conventions. But these rules then must be consistent, complete, and acceptable in context to the individual targets. Autonomy normally leads to better acceptance, because of self-reliant decisions. But in case of saturated and crowded traffic situations, the improvements come from reduction of autonomy and increase in coordinated cooperation. Once a crowded traffic situation is cleared again, one can switch back to autonomy if the situation permits (*101*, *102*). Uncoordinated lane-changing maneuvers directly affects the traffic flow in the network and is a precursor for crashes, especially on highways/freeways. With human drivers, vehicle motion, depends on the reaction time and actions such as moving the foot from throttle to brake pedal, steering, etc. In adaptive cruise control, the reaction time is reduced, but there still is a large phase delay because of the estimation algorithm needed to translate the discrete range measurements (supplied by sensors on-board) to a metric of change in range over time (acceleration and deceleration of the lead vehicle). CACC utilizes V2I communication, so that the vehicle has information about key parameters like position, velocity, and acceleration. CAVs can adjust their velocity in advance to avoid stop-and-go during the merging process, which causes less delay (*103*). The lane-changing decision-making process at the weaving, merging, and diverging sections were studied in the past by researchers using several tools like rule-based models (*104*, *105*), utility theory based discrete models (*106*, *107*), optimization-based models (*108*, *109*), and artificial intelligence models (*110*, *111*).

Using microsimulations models, Hao et al. (12) studied the vehicle positioning during lane change maneuvers at weaving sections using the concept of mandatory lane change and discretionary lane change. While mandatory lane change is a necessary lane-changing behavior to achieve a certain demand, such as merging and diverging, discretionary lane change is an unessential lane-changing behavior, usually to achieve expectations speed or keep a certain distance from the vehicle in front. The study introduced a new concept called lane-changing pressure to analyze the mandatory lane change stages incorporating the driver's preference for lane-changing positions in the weaving section (see Figures 15 and 16).

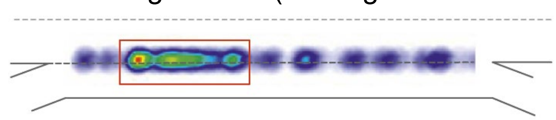


Figure 15 Lane-changing location heat map. Source: Hao et al. (*112*)

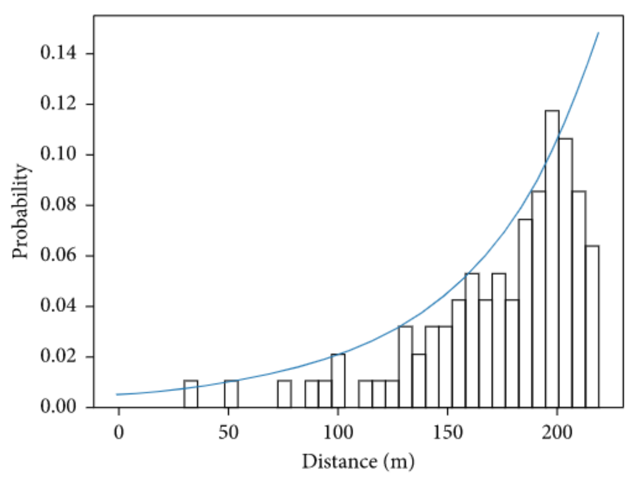
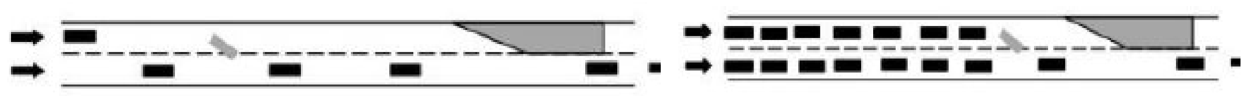


Figure 16 Histogram of lane-changing position. Source: Hao et al. (*112*)

VISSIM microsimulation tools was used to study the impact of different level 3 penetrations on the throughput of weaving segments under late and early merge strategies, capacity drop (see Figures 17 and 18) and the best exiting strategy in low connectivity condition (*113*). Early merge means that vehicles will complete the merge action before the merging point, or the exit point. For late merge, vehicle merges until necessary condition in their routing decision. This merging pattern allows maximum use of road to accommodate upstream vehicles. With the proper use of late merge could improve the vehicle throughput significantly and reduce the queue length up to 50%. Other merge strategies like static merging and dynamic merging are difficult to model using microsimulation tools. For various market penetration, early merge strategy has a dominant advantage in increasing capacity at each penetration level and produces significantly less capacity drop (see Figure 19).



a) b)

Figure 17 Early merge Vs Late Merge represented by a) 200 m and b) 500 m capacity.

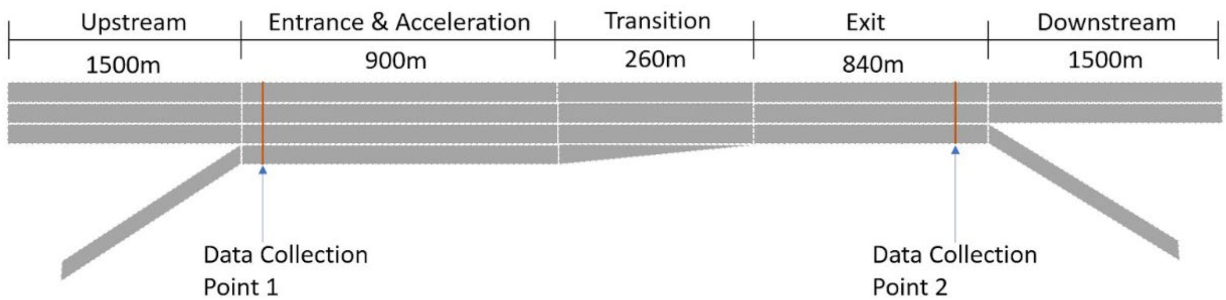
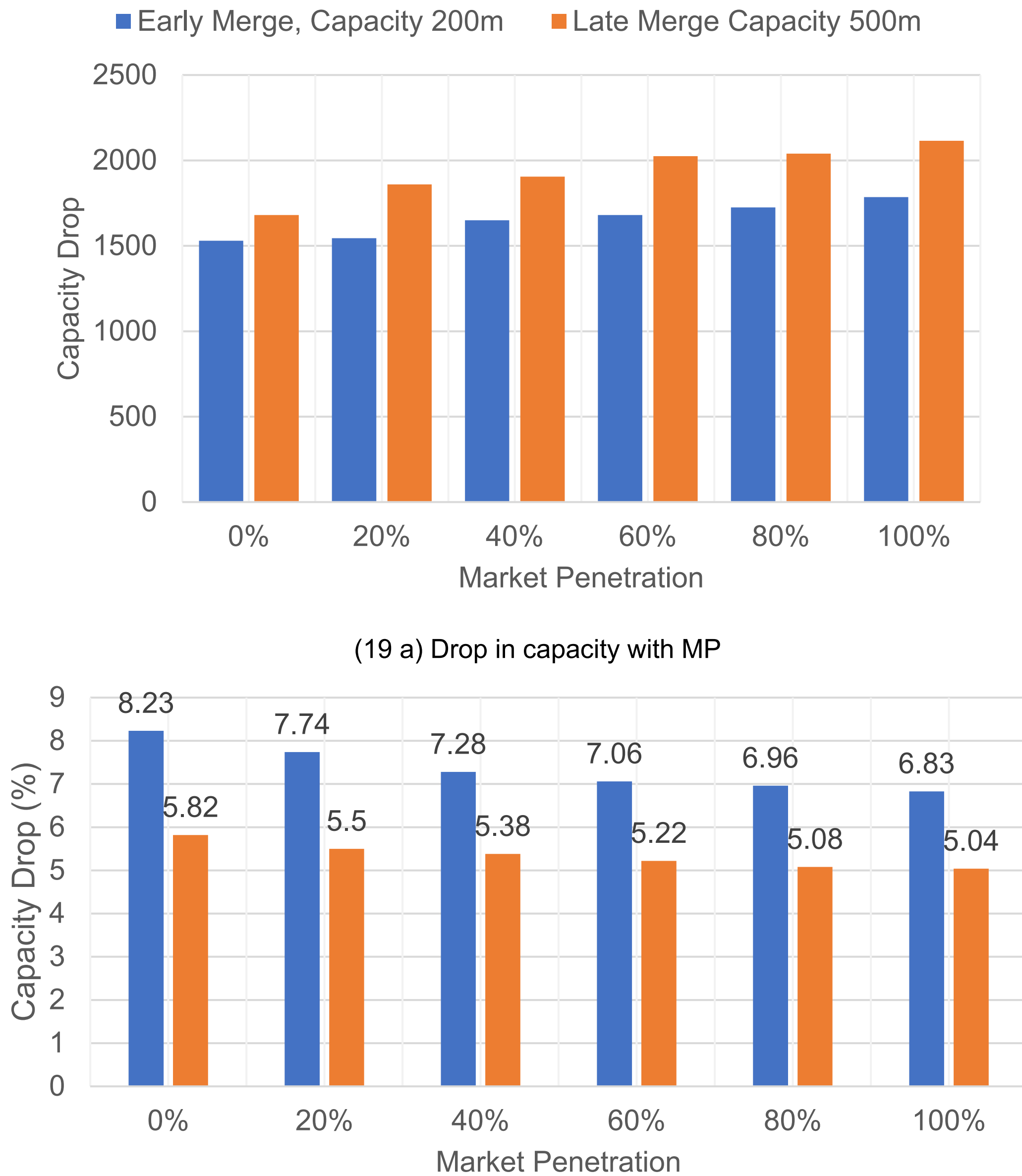


Figure 18 Simulation network and scale. Source: Xu (*113*)



(19 a) Drop in capacity with MP

(19 b) Precentage drop in capacity with MP

Figure 19 Comparison of capacity and percentage capacity drop for early and late merge

On-ramp merging areas are primary locations for bottlenecks due to the mandatory lateral conflicts creating vehicle's maneuver. Speed modulation on freeways and highway on-ramps is considered one of the most challenging scenarios especially when the system consists of a mix of conventional vehicles and CAVs. The management of mixed traffic scenario is an inevitable problem during the process of CAV development. The objective was to coordinate all vehicles passing the merging zone safely and to mitigate the stop-and-go operations under mixed traffic conditions, where both CAVs and conventional vehicles travel on same roads. Ding et al. (*103*) developed a hierarchical cooperative merging framework and investigated the penetration effect of CAVs and AVs on cooperative on-ramp merging, on throughput, delay, fuel consumption and emission for different traffic demands (vehicle cooperative merging problem shown in Figure 20). It was observed that, the average delay was reduced by about 45% when the penetration rate of CAVs reaches about 30%. Under high traffic demand (arrival rate = 0.25 vehicles per second), the congestion becomes severe with low CAV penetration and the average delay can be reduced by nearly half with about 50% of CAV penetration. The decreasing trend is relatively steep when the CAV penetration ranges from 50 to 100%, which means that the majority of CAVs work in a full coordination mode to reduce the travel delay. Under high CAV penetrations, the coordination policy makes better use of the cooperative control zone, which reduces the travel delay during the merging process (see Figure 21).

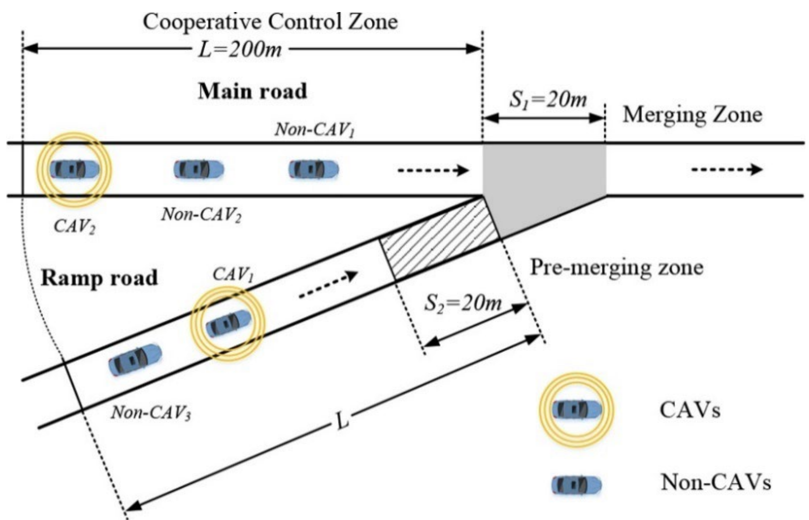
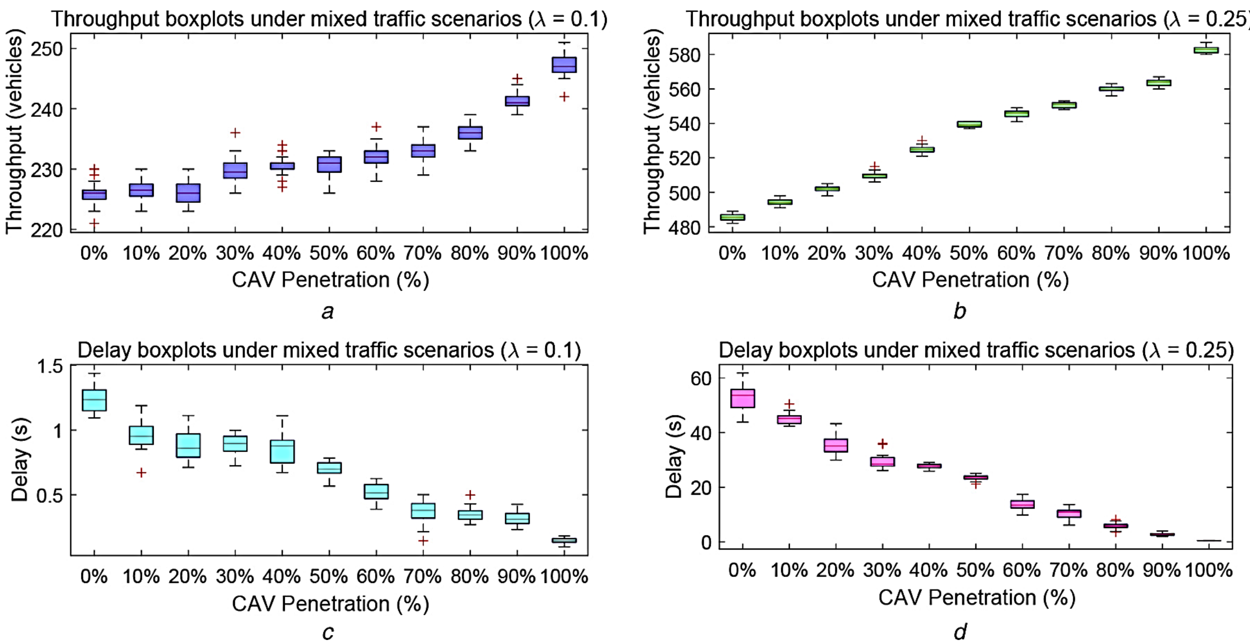


Figure 20 Diagram of vehicle cooperative merging problem. Source, Ding et al. (*103*)



(a) Throughput under low traffic demand, (b) Throughput under high traffic demand, (c) Delay under low traffic demand, (d) Delay under high traffic demand

Figure 21 Throughput and delay under different CAV penetrations and different vehicle arrival rates (λ). Source, Ding et al. (*103*)

Method presented in study by Ding et al. (*103*) can be extended to evaluate spatially the impact of CAV technology on the rate of utilization of road section for such lane changing behaviors which can be further used for modifying the exiting road design layout for similar sections. For instance, large merging and weaving sections could be optimized to provide improved facilities that could cater to the need of the rapidly changing future of the transportation system.

Roadway Design Recommendations

Lane Markings: The lane markings must be wide enough (preferably 6 inches) and must be maintained at high standards for clear detectability under machine vision. Further, all the DOTs must have uniform specifications on lane markings to make interstate travel possible.

Capacity changes: Vehicle automation can reduce time headway, decrease lane widths, and improve the capacity of a segment. However, under mixed traffic conditions, excessive reduction in lane widths would lead to the slowing down of conventional vehicles.

Dedicated lanes: Estimate the market share before dedicating a lane to AVs. At lower market penetration levels, AVs sharing with HOVs was found to produce network optimum rather than the dedicated AV lane. Dedicated lanes were only found to have a significant impact at high market penetration levels (greater than 40%).

Platooning: Vehicle platooning especially truck platooning can have negative effects on pavement stability. Hence, optimal spacing of vehicles in a platoon including the transverse distance is determined before platooning is implemented on the field.

Road infrastructures: The current road infrastructures are not ready to welcome AVs (V2V, V2I communication). They must be upgraded to accommodate AVs and for the smooth transition from conventional driving to automated driving.

Lane width: The current standard for lane width (12 feet) may be reduced due to the capacity improvement capabilities of AVs. Various concepts of road-diets (lane width reduction, bi-directional lanes, etc.) can be developed and the excess space can be converted into sidewalks, dedicated bike lanes, open green spaces, etc.

Transition phase: The most challenging yet important phase is the transition phase (when both AVs and conventional vehicles are operating together at the same time and sharing the same ROW). Special design considerations must be adopted (like reduction in lane width due to AVs but without hampering the smooth operation of conventional vehicles).

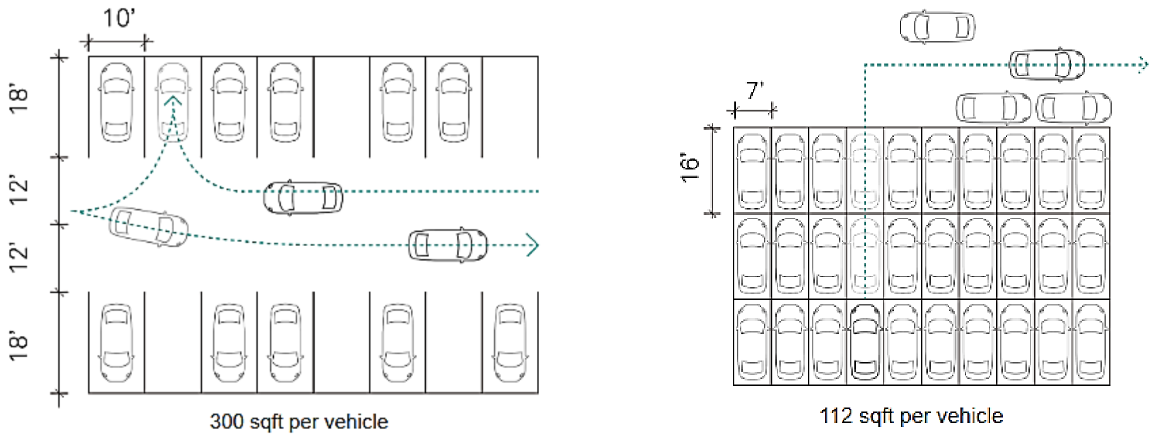
SSD and length of vertical curves: Calculation of SSD and length of vertical curves is dependent on the characteristics and capabilities (braking, headlight, the position of sensors, etc.) of the design vehicle. Since the AV industry is still developing, a design standard must be followed by the various manufacturers to prevent discrepancies in the geometric design of future roads.

PARKING DESIGN AND DEMAND ESTIMATION UNDER AV

At present, vehicles occupy large volumes of space in urban locations and on average they spend more than 95% of their time unoperated in garages, parking lots, or on street parking (*114–117*). As per Hawken, “The contemporary vehicle is not a driving machine but a parking machine”(*118*). The average time spent for finding parking at most activity destinations is also significantly high compared to the actual trip time. The average vehicle is 80% unoccupied when it is being driven by a single driver. And most of the day, vehicles are sitting unused. That, of course, requires space for parking: There are a billion parking spots across the US, four for every vehicle in existence. Plus, there are all the paved roads crisscrossing our cities. Downtowns give 50 to 60% of their scarce real estate to vehicles (*116*). In the long-term however, AVs are likely to reduce the number of vehicles in use. This means that the vast areas of land, previously used for parking will become available. The properties and potential uses of autonomous transport modes affect land-use and urban planning, influencing parking demand and organization, and the attractiveness of neighborhoods as places to live, shop, or work (*119*). Fagnant and Kockelman (10) observed an estimated savings of $250 in parking cost for each new AV in the market, primarily through reallocating parking space from Central Business District (CBD) to more remote areas and from ridesharing. Nourinejad et al. (5), using high-level strategic design found that AV parking can decrease the need for parking space by an average of 62% and a maximum of 87%. The AVs will allow land currently used for transport and parking to be converted to other uses, promoting active modes, such as walking or cycling, or construction of greener space etc. Self-driving vehicles will change parking demand and parking trend in the urban and rural centers. Parking demand refers to the amount of parking that is estimated to be used at a particular time, place, and price. Parking demand will be influenced by vehicle ownership, trip rates, mode split, parking duration, geographic location (i.e., downtown, regional town center or suburban), the value of travel alternatives, type of trip (work, shopping, recreational), and factors such as fuel and road pricing. There are usually daily, weekly, and annual demand cycles. For example, parking demand usually peaks on weekdays at office buildings and on weekend evenings at theaters and restaurants. Parking demand can change with transportation, land use and demographic patterns. For example, a particular building may change from industrial to residential or office use, neighborhood demographics and density may change, and the quality of transit service may change, all of which affects parking demand. Different types of trips have different types of parking demand, and different types of parking facilities tend to serve different types of trips.

Parking Behavior and Parking Facility under AV

Empty repositioning trips are distinct behavioral aspect of AV where AVs can make empty trips to avoid parking at the destination or make the vehicle available to other household members. Repositioning trips are likely to travel in the opposite direction than most person-trips. In short, with AV, there is no need to park at user destination, and can return home, park remotely, or even cruise around. It is expected that the fully AVs can be repositioned to avoid parking costs, that influences the destination and/or mode choice decisions. For instance, travelers currently may be forced to pay large parking costs at their destination, especially if their destination is in the CBD. An AV owner can have their vehicle drop them off at the destination (at the parking entrance or at a designated drop-off zone), then send the AV on an empty repositioning trip to reduce or completely avoid parking costs at their destination (*120*). Considering the land value, constructing large parking facilities for AVs outside the city centers and encouraging AV owners to park their vehicle at such parking facilities by choosing appropriate parking costs at each location, will be help in converting parking in CBDs to commercial or efficient spaces (*121*). The demand for parking in the main CBD is moved towards a less intensive economic activity areas, so that land in business districts can be utilized more efficiently (*122*). This way, demand for on-street parking at a short distance from the final trip destination is expected to decrease, freeing space for other land uses, especially for congested areas with low on-street parking supply and high demand during peak periods, provided additional vehicle miles will be traveled. While a conventional vehicle requires an average of 300 square feet parking space, the driverless vehicle only requires 112 square feet parking space per vehicle (*123*, *124*), as shown in Figure 22. The AV can park in a smaller parking spot without any collision with the adjacent vehicle. The layout of the parking lots has a great impact on space efficiency. The average width of a parking spot in the US is between 8 and 9 feet due to the need to safely move drivers and passengers in and out of vehicles. Existing layouts divide the parking into several islands and roadways. The islands are used to store vehicles while the roadways separate the islands and allow vehicles to maneuver when searching for a desirable spot.



(a) Conventional parking lot (b) Self-driving parking lot

Figure 22 Conventional and driverless parking configuration

Compared to regular parking facility that have only two rows of vehicles in each island, AVs can have multiple rows of vehicles stacked behind each other and roadways can be narrower (see Figure 23). The smart infrastructure of such parking facilities controls the physical maneuvering of the vehicles. Although this multi-row layout reduces parking space, it can cause a blockage if a certain vehicle is barricaded by other vehicles and cannot leave the facility. Research also indicates that AV will have three narrow driving lanes different than the conventional vehicles because the third lane will be an inter-island gap which serves as a buffer zone or a waiting area. For instance, (see Figure 24), the blue vehicle wants to leave but it is blocked by two green vehicles ahead of it. At this situation, the best approach is to provide a space, an inter-island gap, where the two green vehicles could stay, allowing the blue vehicle to leave (*117*, *124*). The spatial efficiency of AV parking is also a consequence of their precise parking /parking related transitional movements. As opposed to the conventional vehicle, which is parked 95% of the day; the self-driving, autonomous vehicle is expected to work most of day and rest during the night, creates a temporal shift in the parking trend (see Figure 25). Off street parking infrastructure can redesigned to form vehicle hub which will function as a place of rest for the AV also provide flexible programs and spaces for the users at the same time.

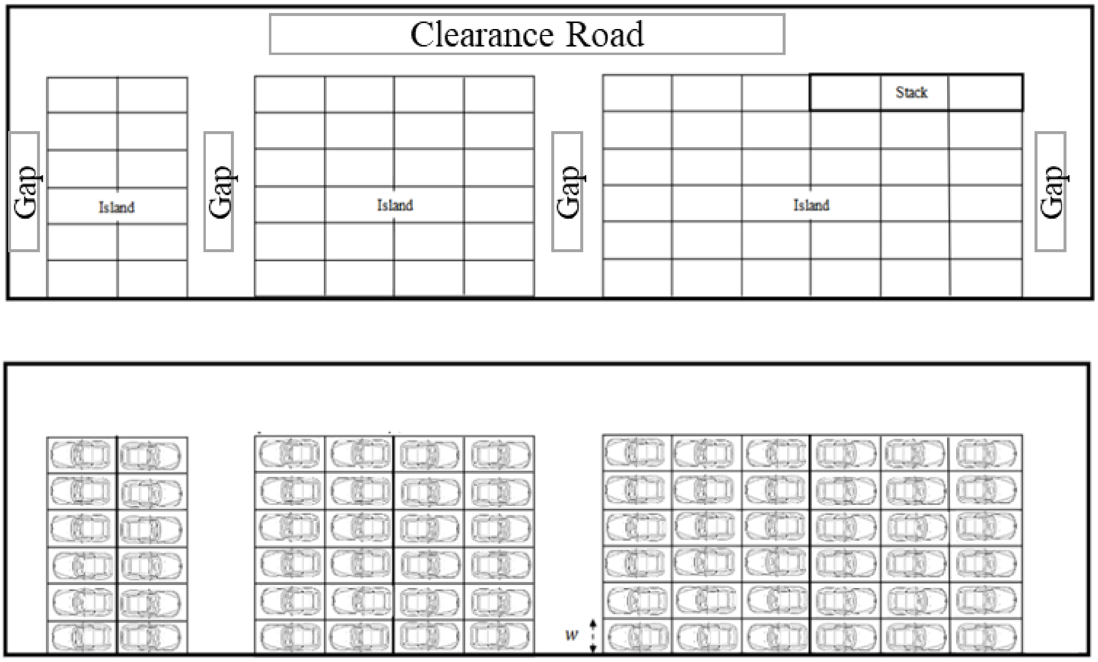


Figure 23 Layout of gaps and islands for exclusive AV parking. Source: Nourinejad et al. (5)

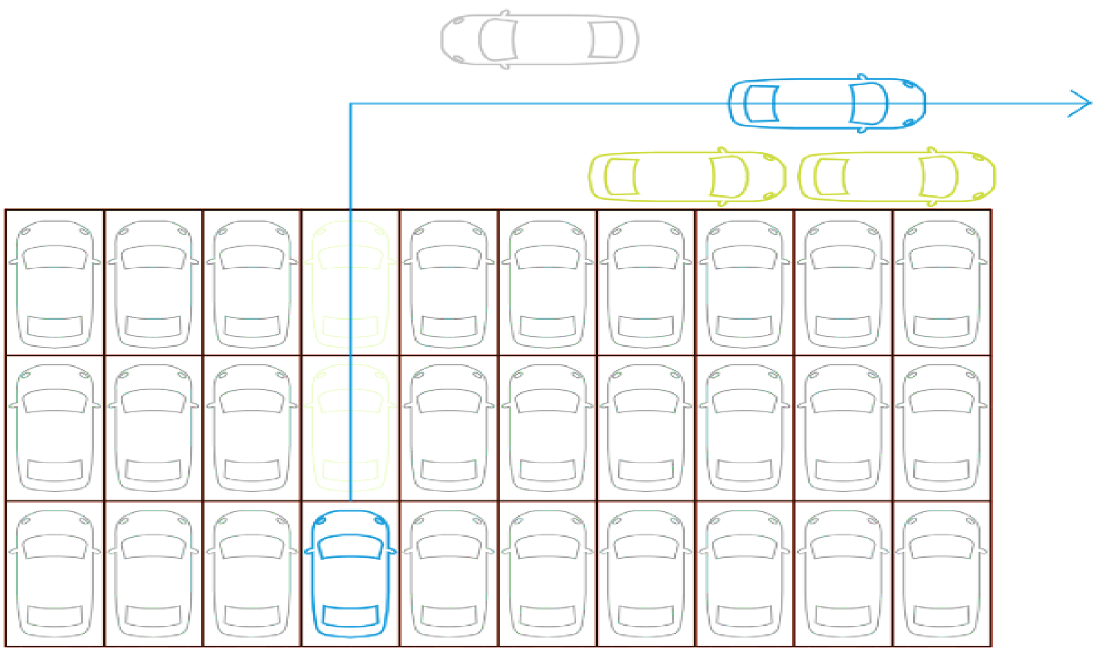


Figure 24 Reallocation at inter-island gap
Source: Beyond the Autonomous Vehicle: The New Mobility Hub (*124*)

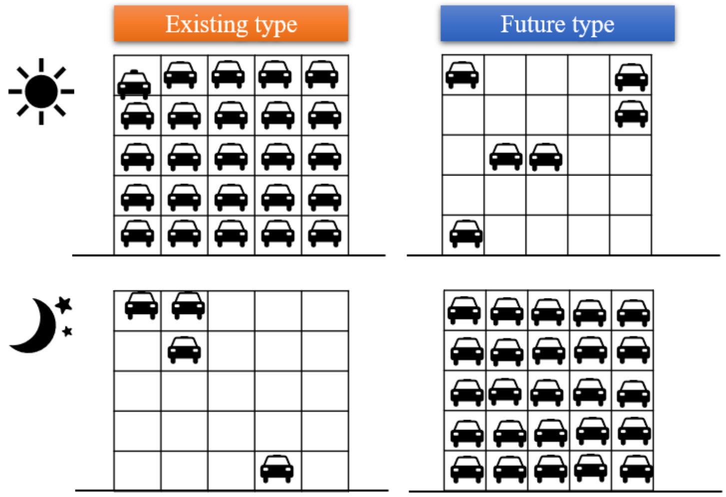
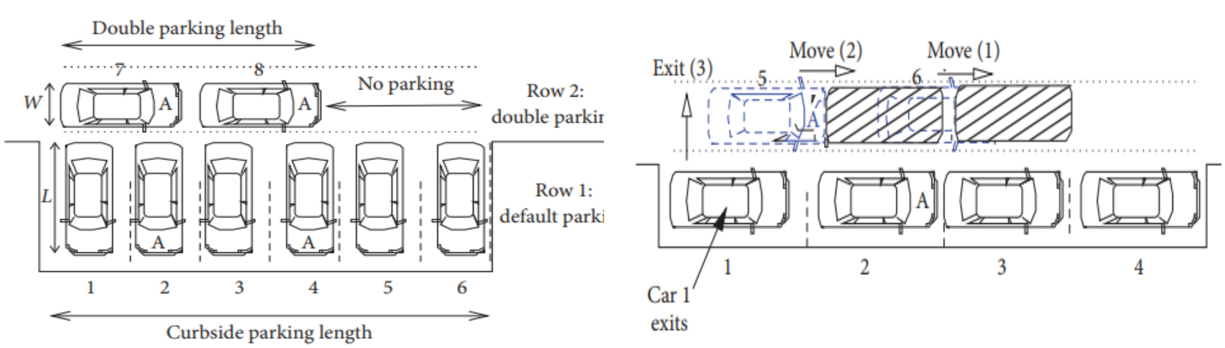


Figure 25 Expected parking behavior changes at parking facilities. Source: Beyond the Autonomous. Vehicle: Source: The New Mobility Hub (*124*)

In large metropolitan cities double parking (parallel or perpendicular) is a common way of parking within a stall or in streets, as shown in Figure 26. Double parking can temporarily increase the supply in locations where the city cannot offer better solutions during peak hours. Double parking usually exhibits temporal and spatial patterns, happening spontaneously in destinations that attract many people, but which have a shortage of parking for peak demand (e.g., school drop-off/pick-up times, concert hall, load/unload, and market). Parking returns to normal state after the event or activity is over (*125*). If unattended, it can also foster traffic congestion and accidents when parking is done alongside another vehicle on the side of the road. Double parking can prevent another person, the one who is adequately parked, from being able to leave when they need to since they are now blocked in. The new capabilities offered by AVs, could mitigate such safety concerns, nuisances associated with this practice to a large extend. Estepa et al. (*125*) analyzed the case of storing AVs in double-parking locations alongside rows of parking spaces whose occupying vehicles would be "blocked in"; the impact ascribed to AVs arises from an assumption that they would be able to communicate and maneuver as necessary without human control to allow a blocked-in parked vehicle to exit.



(a) Perpendicular Parking (b) Parallel Parking

Figure 26 Double Parking configuration. Source : Estepa et al. 2017 (*125*)

Private AVs and Shared AVs Mobility Model

The impacts on urban form can differ greatly depending on the type of AVs introduced, the extent to which they are shared system and the introduction of supporting policies and infrastructure. The impacts of different types of AVs (from individual pods to driverless trains) on future urban form are scarcely addressed in the previous studies. As different business models of AVs, including Shared AVs (SAVs) and Private AVs (PAVs), will lead to considerably different changes in regional vehicle inventory and VMT, anticipating the direction of the technology maturation, and resulting impact on the built environment becomes very critical as far as city planning is concerned. Nevertheless, government at both local and federal level must review their city planning strategies in the light evolving AV technology to be more resilient to cope with the uncertain future that AV holds. A 2015 study by National League of Cities (NLC) found that only 6% of cities' long-range transportation plans acknowledged the prospect of AVs for their city (*126*, *127*). To capture the possible future transformations in the urban parking and land use due to AV, the city planning committee must reassess their existing parking demand prediction models or develop new models by incorporating the AV as new mode, considering both shared and private AVs. Future design of AV parking facilities must ensure optimized movement of vehicles within the lot, technology/communication issues and smooth transfer of data. For instance, underground parking sites can block the GPS signal, data transfers, connection to cloud to name a few. With conventional vehicles, users prefer to park near their destinations, which leads to asymmetric distribution of vehicles during peak hours, making it difficult to find a shared vehicle. In a personal mobility model, automobiles continue to be private mobility resources, parking demand might drop far less dramatically, though the space required to store private vehicles still might shrink (*126*, *128*). As these vehicles can also automatically cruise to more affordable parking spaces after dropping owners off at trip destinations, PAVs will alter the spatial layout of parking spaces in cities, as AV will bring about a change in the decision-making process of location choice and destination and transport mode selection. PAV are expected to alter the spatial distribution of parking space in cities and does not contribute significantly in reducing parking spaces (*122*). Existing literature also emphasizes on the negative externalities of personal mobility model, which includes additional VMT generation, leading to more emissions and more transportation energy consumption produced primarily due to travel behavior changes (*129*–*131*). Moreover, vehicles are driven by an operator (not the traveler). Driver salaries increase the cost of service (*120*, *132*). AV technology will open new alternative parking strategies for locations with paid parking/restrictions. They could certainly continue to park as conventional vehicles currently do at free parking spots. In a shared mobility model, automobiles become shared mobility resources that are on the road, rather than in a parking lot, for most of the day, which might considerably reduce the parking demand. By replacing private vehicles, shared AVs would reduce traffic volume, free up land currently used for parking spaces, and improve transportation access for disadvantaged social groups (*126*, *128*). As discussed earlier, AV enthusiasts believe and hope that AVs will bring attractive prospects for most people to give up private auto ownership in favor of "Transportation as a Service." They also promote the idea of trips to be shared as much as possible, like Uber Pool and Lyft Line, or in public buses. With pricing, time advantages, and locational advantages for shared rides, maximizing sharing is central to realizing many of the potential AV benefits. Results from several simulation studies in the past have shown that SAVs can significantly curb the demand for parking space by reducing vehicle ownership (*19*–*21*). SAVs are expected to be the likely choice for future urban travel. Consumer surveys indicate continued growth potential for shared mobility (see Figure 27). Policy shifts, changes in behavior, and new transportation offerings will influence users' choices, too. As the time for finding parking and walking time from the parking area to destination is eliminated, the value of time for driving AVs is different from that for driving non-AVs, which could impact on travelers' route/destination choice behavior. Once AV overcomes the limited accessibility and current reliability of car-sharing/ride-sharing programs, they will facilitate car-sharing and ride-sharing behavior, maximizing the benefits to the system (*132*, *135*, *136*).

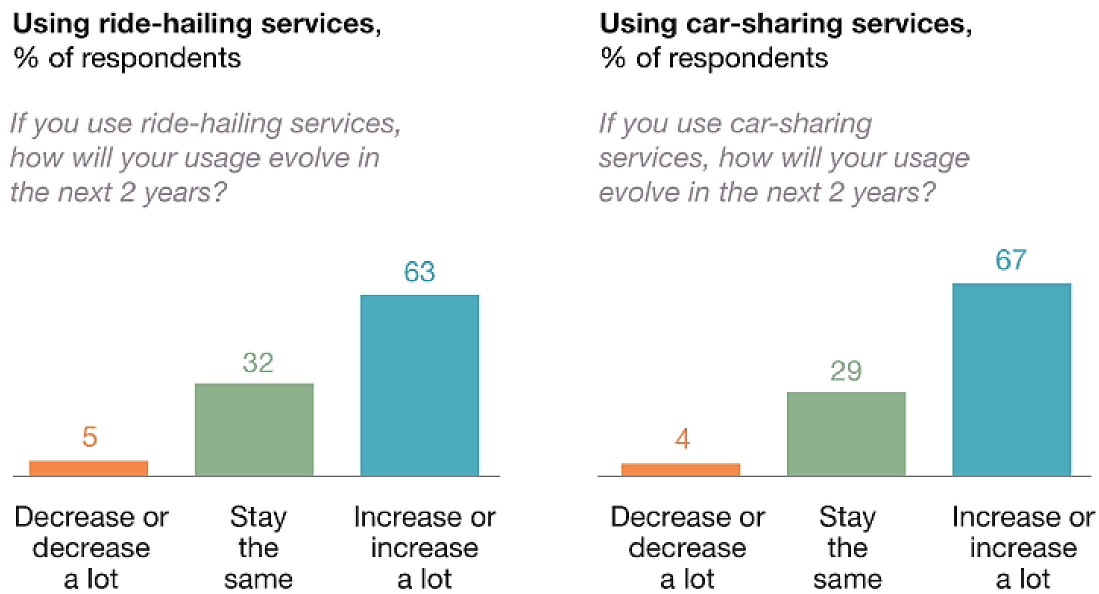
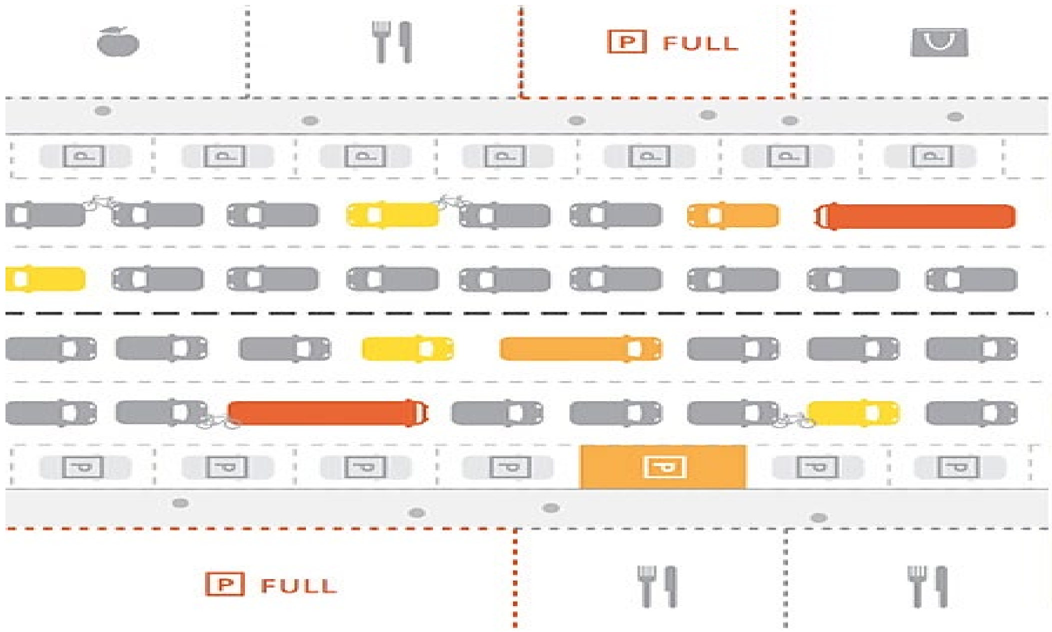
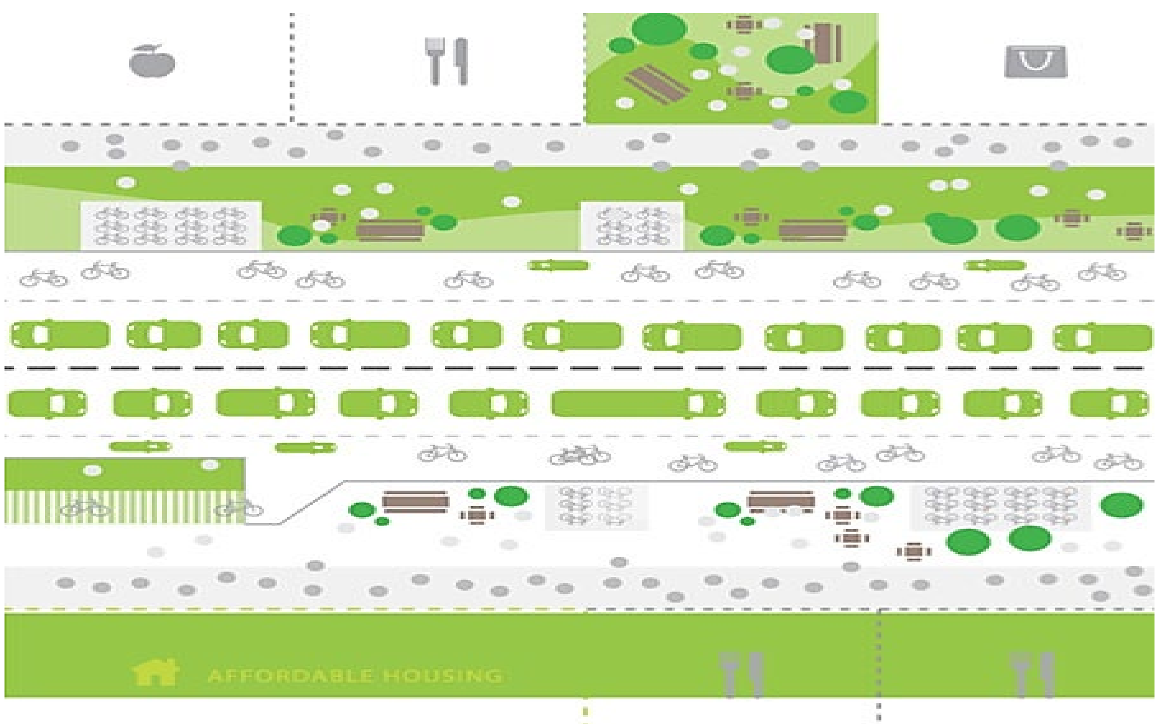


Figure 27 Public response to shared mobility services. Source: McKinsey & Company (*137*)

The Mobility on Demand (MoD) integrates multiple transportation options into one accessible, on-demand system that provides door-to-door mobility service. It is an appealing transportation concept that is envisioned to provide an alternative to private personal vehicle ownership through the sharing economy. MoD coupled with AV technology services are expected to significantly reduce the public parking demand or even make structured parking obsolete by improving vehicle utilization rates (*133*). SAV Systems, which will operate as a taxi service on demand, allowing related/unrelated passengers to share the same ride with minimal increases in travel time and costs. It is reasonable to expect that SAVs will operate with a higher passenger load and automatically navigate to locations from where trips will originate, thereby reducing parking demand (*132*). Autonomous mobility-on-demand solves the repositioning issue by realizing that AVs can reposition empty, offering low-cost taxi service. The broader use of shared mobility (as expected by recent study (*137*)) with AVs will lead to decreased traffic, pollution, and travel time. Several studies have explored through simulations the role of shared mobility services either as additional service in the mobility market, or by fully deployed systems that would replace all motorized mobility in a city. Several other studies in the past have investigated the replacement of all or a specific share of current private vehicle trips by SAVs and suggest that this could significantly reduce the number of vehicles to process the current transport demand, regarding the replaced trip, and additional reduction, if ridesharing is also assumed, implying reduced parking needs, for instance, see Figure 28.



(a) Streets currently occupied by vehicles and street parking



(b) Shifting to shared AVs, more area could be reclaimed for parks and housing

Figure 28 San Francisco's Smart City proposal, SFMTA. Source: Vox (*116*)

Modeling Approaches in Parking Search Study

There are several types of parking-related models with different purposes, such as design of a parking facility, optimization of parking entrances, or representation of interactions between users and parking. Existing literature presents various modeling approaches to analyze the parking search. Research on parking behavior appears approximately split between (a) discrete choice model: parking behavior is treated as a distinct factor that affects individual travel choices, (b) network models: parking is presented as one element of a traffic network system, (c) simulation models: model has its basis in modifications to existing models and incorporates a parking system's interactions and feedbacks and (d) performance and design models: traffic movements inside a parking facility are simulated microscopically (*138*). Nourinejad et al. (*117*) classified AV parking design stream into three categories as stacking problem, parking assignment and optimal layout design. Stacking problem involves optimization of AV movements within the parking facility to minimize the number of relocations whenever retrieving a blocked vehicle. Parking assignment generally involves modeling search behavior or developing models that assign parking spaces to vehicles in an optimal fashion. Parking assignment also appears in the AV parking design problem. The challenge is to assign the vehicles to the islands of the carpark in a balanced way. And for optimal layout design, the objective of the AV parking design problem is to find an optimal layout having least relocations with components that include islands and driving lanes/gaps.

Nourinejad et al. (*117*) evaluated the impact of AV on the design of parking in the future using mixed-integer non-linear program to modify existing parking facility design to ensure maximum efficiency. The study presents a heuristic algorithm to find a reasonable upper-bound of the mathematical model using Benders decomposition for an exact answer to come up with optimal parking layout with minimum relocations. The result from analysis shows that autonomous vehicle parking can decrease the need for parking space by an average of 62% and a maximum of 87%. This revitalization of space that was previously used for parking can be socially beneficial if parking is converted into commercial and residential land-uses. The study also recommends the use of modified model that considers individual characteristics of each vehicle including arrival time, planned departure time, and vehicle size for finer level operational planning. Knowledge of departure times can significantly influence how the vehicles are arranged in the parking.

Kong et al. (*139*) developed a mixed integer nonlinear optimization model to evaluate the impact of AVs' precise physical maneuvering on the spatial efficiency of surface parking facilities considering three types of parking maneuvers (a) single-motion "front-in" maneuvers (in which the vehicle front enters the parking space first), (b) single-motion "reverse-in" maneuvers (vice versa), (c) "front-in" maneuvers with multiple "toing/froing" motions, (d) "translation" maneuvers that require the rear wheels to pivot independently of the front wheels (which standard contemporary automotive design does not accommodate) and facility sizes from 100 ft × 100 ft (10,000 sq ft) to 1000 ft × 1000 ft (1,000,000 sq ft), including both square and rectangular shapes of a surface parking facility. Their optimization framework calculates the number of parking spaces that can be accommodated within a single-level facility of a given length and width. They found that for both conventional and AV operations, the spatial efficiency increases with facility size (but subject to diminishing marginal returns) and that the sensitivity of efficiency to 1′-increment increases in facility size decreases with facility size.

Focusing on the city of Berlin in Germany, Bischoff and Maciejewski (*140*) used microscopic simulations techniques to quantify the effect of AV on replacing conventional vehicles. The synthetic population used, depicts a typical weekday in Berlin. For the autonomous taxi scenario, the model was simulated with fleets of sizes between 50,000 and 250,000, incremented by 10,000. Simulation results recommend that a fleet of 100,000 vehicles will be enough to replace the vehicle fleet in Berlin at a high service quality for customers, one autonomous taxi could replace the demand served by ten conventional vehicles in Berlin. Similarly, Correia and van Arem (*141*) presented a User Optimum Privately Owned AVs Assignment Problem (UO-POAVAP) and tested it for one small city in the Netherlands, Delft. They developed a cost-minimization trip assignment problem with respect to mode choice, departure time and route choice, using trips of families who travel inside the city during a whole working day in the year 2008. The cost of AV was determined by considering the driving and parking costs incurred by their use. The research provides a solid methodological framework for studying how replacing privately owned conventional vehicles with automated ones affects traffic delays and parking demand in a city. One drawback of using past trip data for such study is that traffic flows which are observed in the network cannot be validated.

Several recent macroscale travel-forecasting efforts have attempted to quantify the combined effects of AVs on all aspects of the transportation system, including parking impacts. Wang et al. (*142*) developed a microscopic simulation to determine the impact of curbside parking bay design on high-occupancy SAVs (more than four seats). The study shows that the provision of sufficient curbside bay areas for SAV loading and unloading can have a positive impact on reducing operating costs and average waiting time, thus improving client experiences.

Gu et al. (*143*) developed a macroscopic parking dynamic model for parking-dense neighborhood in the southeast of Sydney, Australia. The macroscopic parking dynamics model was developed wherever off-street parking is explicitly considered with limited capacity and interacts dynamically with on-street parking. The model optimizes the expected aggregate cruising delay considering both on street and off- street parking. Two real-time parking pricing strategies were developed and integrated with the parking model, one being a feedback or reactive approach and the other a predictive or proactive approach. While reactive pricing is admittedly less data demanding and thus more operable in practice, its deficiency was highlighted through extensive numerical experiments which mainly arises from the feedback delay especially in the presence of fast varying parking conditions. As a result, proactive pricing consistently offers a better overall system performance thanks to its predictive capability, although requiring extra effort to acquire and calibrate the input (*143*).

Levin et al. (*120*) using genetic algorithm modeled empty repositioning behavior of AV and further developed a modified multiclass static traffic assignment that combines route choice with a logit model for parking location choice, in which the AV passenger-carrying trips can create a second empty repositioning trip to an alternate parking zone. Both AVs and conventional vehicles were considered in the analysis. While conventional vehicle travel from origin to destination and park at destination, AV travels from origin to destination and can choose to reposition empty to alternate parking facilities. Results indicated that adjusted parking costs are effective at reducing the congestion caused by empty repositioning and encouraging more optimal parking choices for repositioning AVs. Parking demand changes with time and location. Numerous existing literatures discussing AV parking estimation models have used a static parking demand, which is fixed throughout the study period. Such studies also highlighted the importance of using dynamic parking demand instead, as the facility can have more than one most efficient layout (*117*) while dealing with dynamic parking demand. There is enough evidences that modeling congestion dynamics and its causal relationship with cruising-for-parking and parking pricing is a major challenge that necessitates further investigation(*143–146*).

Zhang et al. (*131*) built a model to explore the impact of PAVs on regional vehicle inventory for Atlanta metropolitan area using greedy algorithm and Mixed Integer Programming (MIP).Model results show that only 18% of households can reduce vehicle ownership by sharing private autonomous vehicle among household members. The regional household vehicle ownership may only be reduced by 10% if households switch from conventional vehicles to private AVs. As PAVs can relocate from the trip destination to park somewhere else to save parking costs, the spatial configuration of parking spaces is going to change fundamentally. Similarity, Wang et al. (*122*) deployed linear programming optimization model to optimize spatial configuration of parking space for PAVs. The models minimize the cost function that is dependent on construction, maintenance, and opportunity costs of city-wide parking lots. The model results indicate that the demand for parking in the City of Atlanta may concentrate in Traffic Analysis Zones (TAZs) with less intensive economic activities, so that land in business districts can be utilized more efficiently.

Numerous recent literatures on the AV parking demand estimation have focused on the popular agent- based models and techniques. Though Agent-based models are undoubtedly the finest with the most details, it comes with a high computational cost. Agent based models can augment discrete behavioral changes to agents so that individual behavior of people with potentially different preferences can be effectively captured. Here, instead of looking at aggregated traffic flows along roads, individual people/drivers called “agents” are simulated and tracked (*132*, *133*, *147–149*). An early and important study focusing on parking model is by Waraich and Axhausen (*147*), where the parking choice was modelled using agent based simulation technique. The objective of the study was to capture individual valuation of time and differences in taste. The agent-based parking choice was implemented into an existing travel demand simulation framework to large scenarios with large number of agents. The model considers four types of parking: public parking, private parking, peserved parking and preferred parking (e.g., a person driving an EV might require a parking space with a power outlet for charging). The agent-based simulation optimizes the utility function/cost function and results of a scenario from the city of Zurich demonstrate that the model can capture key elements of parking, including parking capacity and pricing and is able to provide help for designing parking focused transport policies. The dynamics involved in the parking choice behavior modelling using agent-based simulation inherited from Waraich and Axhausen (*147*) is illustrated in Figure 29. The parking model provides feedback to traffic simulation, as such the whole simulation can react to spatial differences in parking demand and supply.

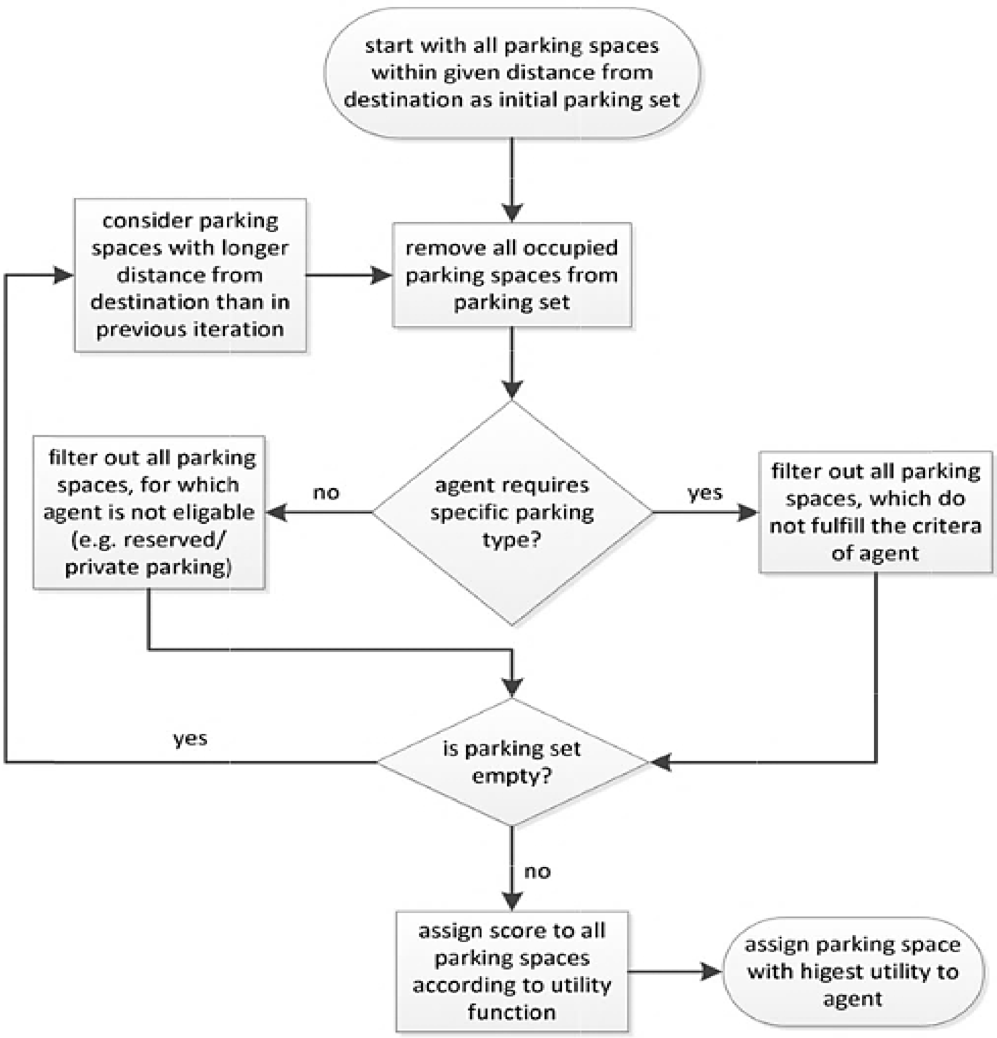


Figure 29: Parking choice dynamics. *Source:* Waraich and Axhausen (*147*)

Burns et al.(*150*) developed an advanced agent-based simulation model to evaluate the impact of SAV system on various parking scenarios. They examined a shared, self-driving and centrally dispatched fleet of vehicles in three different environments: a mid-sized US city (Ann Arbor, Michigan), a low-density suburban development (Babcock Ranch, Florida) and a large and densely populated urban context (Manhattan, New York). It used travel survey-based data on average trip distances, trip-making rates (e.g., trips per hour) and travel speeds to help characterize travel in the regions studied. A combination of queuing, network and simulation models was used to calculate travel patterns and vehicle requirements. The modelling system generated trips to be serviced by a fleet of shared AVs via a centralized dispatching system that keeps track of the locations of all vehicles. The origins and destinations of trips are generated randomly over the whole of the region. Trips are requested at a constant average rate, times between requests are exponentially distributed and the single class of vehicle used in the model operates at a constant travel speed. The results showed that the cost per trip mile can range from $0.32 to $0.39, which is more affordable than existing private vehicles.

Chen et al.(*151*) developed an agent-based regional time discrete model to study the management of a fleet of shared autonomous electric vehicles (SAEVs). The study integrated the

EV charging component into the model to analyze the spatial layout of charging stations for the shared autonomous electric vehicle system. The simulation examined the operation of SAEVs under various vehicle range and charging infrastructure scenarios in a gridded city. The hypothetical city was modelled using similar urban densities of Austin, Texas. Simulation results also recommend that the shared fleets can serve 95.6–97.9% of all trips with average wait times between 7 and 10 min per trip, while producing an additional 7–14% of empty VMT for traveling to passengers, strategic repositioning, and accessing charging stations.

Zhang et al.(*132*) used agent-based simulation approach to explore the impact of SAV fleet size, vehicle cruising, and ride-sharing and client's preference on urban parking demand. A 10 mi × 10 mi hypothetical city was considered for the analysis and travel/trip attributes like Trip length and trip departure times were added using estimates from the National Household Travel Survey. People willing to use SAV are the agents. Scenarios with different levels of willingness to share from 25% to 100% with increments of 25% were tested. Simulations were run for 50 simulation days to obtain stable results. The study developed scenarios with fleet sizes between 500 and 800 vehicles, with various levels of willingness for ridesharing, and with different empty vehicle cruising strategies. The simulation model uses a low market penetration rate of the SAV system, assuming approximately 2% of the population within the study area will adopt the system. Each client agent generates several vehicle trips within a simulation day. The trip generation rate for each grid cell was based on the density of client agents given the assumption that each person generates around 3.79 vehicle-trips per day on average (National household travel survey (2009) (*152*)). Additionally, a SAV client match center collects requests from persons requesting a trip and finds an SAV that minimize the cost of providing the service. Results from the simulation study shows that the average waiting time diminishes when more SAVs are added into the system. Larger fleet size in the system resulted in a larger demand gap between the urban center and urban fringe area. The simulations results showed up to 90% elimination of parking demand for clients who adopt the system, at a low market penetration rate of 2%. The results also suggest that different SAV operation strategies and client's preferences may lead to different spatial distribution of urban parking demand. Such studies offer limited information about parking implications for a real city. Modelling assumptions pertaining to such grid based synthetic city parking analysis may not represent the actual field behavior, yet it provides some useful insights for parking demand estimation.

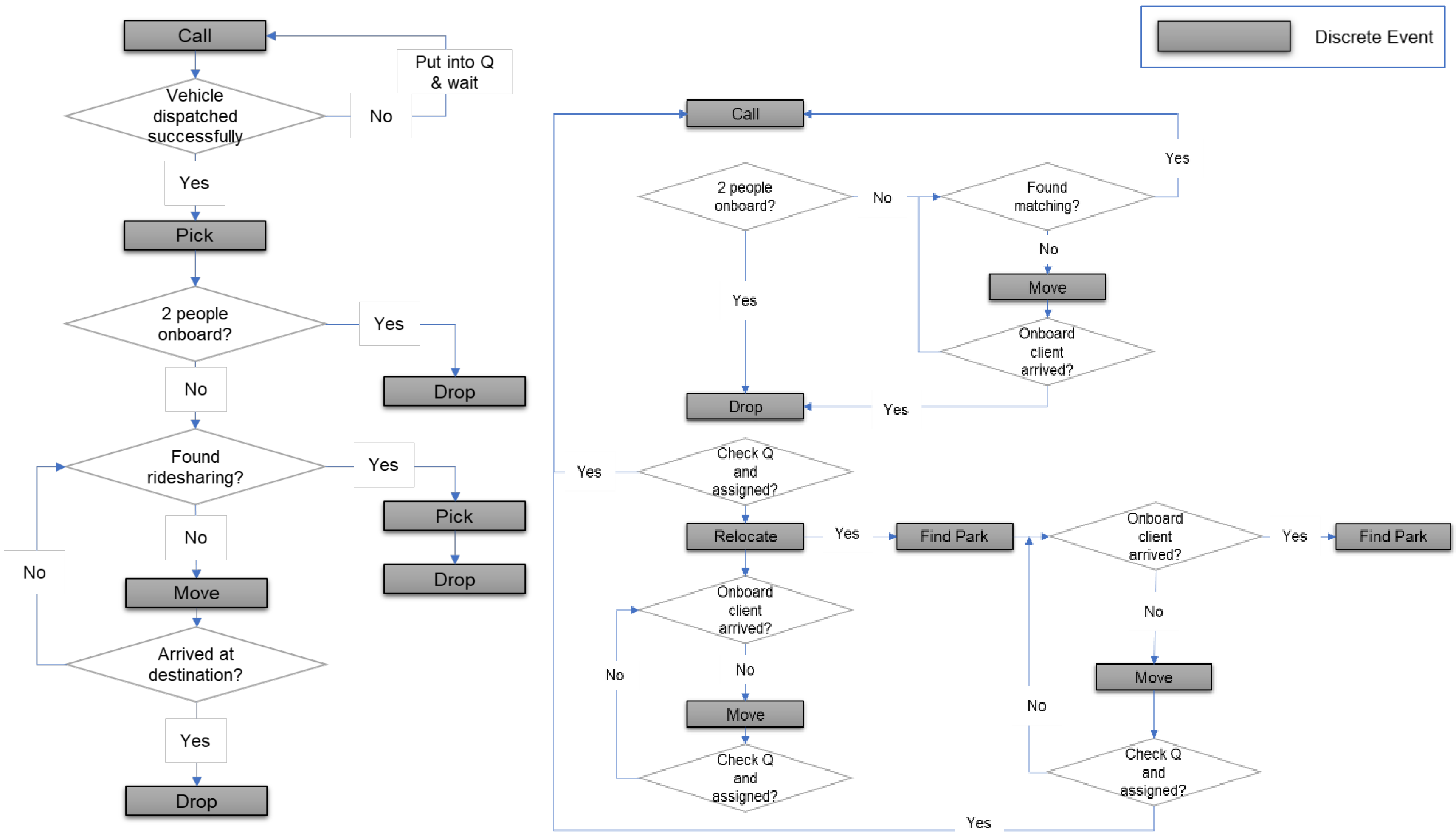
In Lisbon, Portugal, the International Transport Forum (*153*) explored the impact of the AVs on urban traffic with respect to fleet size, volume of travel and parking requirements over two different time scales: a 24-hour average and for peak hours only. They developed an agent-based model that simulates the daily operation of a hypothetical shared mobility system in Lisbon using real trip-taking activity and Lisbon's real road network. A dispatcher system manages the centralized task of assigning mobility requests to vehicles using the location of shared AVs, their current occupancy level, and the location of clients as its main inputs. The model estimated trip routing based on an algorithm that generated the lowest-cost path between any pair of nodes of the network. For testing the shared mobility scenario, their study investigated the *Ride Sharing System* in which travelers share time and space resources by travelling in the same vehicle *simultaneously* up to the capacity limit of the vehicle (may either be privately owned by one rider or from a vehicle fleet company) and *Vehicle Sharing System* where travelers share time resources by travelling in the same vehicle (normally owner by a vehicle fleet manager or peer-to-peer experiments) *sequentially*. The study also considered EV fleet assuming a fast battery recharging time of 30 minutes and vehicle autonomy of 175 kilometers (108.74 miles). The study found out that self-driving fleets completely remove the need for on-street parking in all the considered scenario, which makes up to nearly 20% of the curb-to-curb street space in study city and furthermore, up to 80% of off-street parking could be removed, generating new opportunities for alternative uses of this valuable space. Interestingly, when testing the scenarios with mixed fleets of shared mobility options and conventional privately-owned vehicles, the study observed reductions in parking space requirements to be lower in the *Ride Sharing System* (up to 25%) and even it increased in the *Vehicle Sharing System* in the absence of public transport. These findings suggest that shared and self-driving fleets operating in parallel with private conventional vehicle fleets may lead to even higher parking requirements than today in the absence of public transport.

Adapting the previous work on agent based parking models by working on the study limitations, highlighted in (*132*), Zhang and Guhathakurta (*154*) studied the spatial distribution of SAV parking demand in the City of Atlanta using a discrete-event, agent-based simulation model. The discrete events associated with parking related and parking related transitional decisions are shown in figure 31. The study simulated the operation of SAVs in the city of Atlanta, Georgia, by using the real parking inventory and transportation network with calibrated link level travel speeds, travel demand origin–destination (O-D) matrix, and synthesized travel profiles. The study considered three types of parking scenarios:

- Free parking: SAVs can enter all the existing parking infrastructure if space is available in the lot,
- Entrance-based charged parking: SAVs need to pay an entrance fee whenever they enter the parking lot, regardless of the length of time parked,
- Time-based charged parking: SAVs pay for parking on the actual parking duration upon leaving the parking lot.

The study assumes that SAV system has 4 entities: the vehicle entity, the trip entity, the queue entity, and parking lot entity (see Figure 30). The dynamics of the system is controlled by a list of events related to vehicle entity that occurs in a sequential manner. The study also considered a central dispatching system that assigns the closest available SAV, also, identifies the parking destination with the lowest parking costs including relocation. Parking cost is function relocation, empty travel penalty, parking ticket costs for idling vehicles. The results suggested that parking demand can be reduced by over 90% for households that were willing to give up private vehicles and use SAVs. Nevertheless, the spatial location of parking demand depends heavily on the policies determining the maximum allowed parking, cruising time and the cost of parking. For example, SAV parking tends to concentrate in low-income neighborhoods when parking becomes expensive, which may lead to some transportation equity issues in the era of SAVs. One limitation of the study is that the model considers only SAVs. Zhang and Wang (*133*) developed a more practical, data-driven agent-based simulation setup to study the impact of SAV on spatially and temporally explicit parking reduction trends with mixed travel modes- mix of SAVs, PAVs, Shared Conventional Vehicles, and Conventional Private Vehicles. Most studies have examined the impact of SAVs on parking at one point in time (with various market penetration scenarios). However, it remains unclear what demand reduction trajectory will prevail during the transition period when there will be a mix of PAVs, SAVs, Shared Conventional Vehicles, and Private Conventional Vehicles. There is major gap in information on how quickly the demand for parking space will decrease during the transition period, how much change in the spatial pattern of parking should be expected, and how much time is left for planners to develop strategies to adjust for possible outcomes. Zhang and Wang used the agent-based model for SAV developed earlier(*154*) as base model, and incorporated the PAVs, Shared Conventional Vehicles, and Conventional Private Vehicles. For incorporating Privately-Owned AVs and Conventional Private Vehicles, a new “leave parking lot” event was added to the existing base model. Shared Conventional Vehicles were considered to have the same settings as SAVs. Rather than assuming different market penetration values for AV/SAV, this study used the parameters from the most relevant existing literature on AV market and penetration studies (*155–157*). The results indicated that in the most optimal AV and MoD adoption scenario, the parking demand will decrease by over 20% after 2030, especially in core urban areas. Meanwhile, the parking demand in residential zones may double, which could lead to transportation equity concerns. Parking relocation may also induce environmental issues by generating a considerable amount of empty vehicle miles traveled.

Kondor et al. (*134*) developed a systematic data-driven analysis framework for estimating parking needs and travel of on-demand mobility vehicles including number of vehicles and extra miles traveled in Singapore using agent-based modelling setup for a hypothetical scenario where every person currently using a private vehicle for trips in the city-state of Singapore is willing to switch to shared mobility service. The matching processes used to assign vehicles to trips and parking to vehicles is shown in Figure 31. The results showed that parking infrastructure reduction of up to 86% is possible, but at the expense of a 24% increase in traffic measured as vehicle miles travelled. However, reduction in parking of around 57% is achievable with only a 1.3% increase in VMT. A detailed model of people’s movements in Singapore was extracted from the urban mobility simulator, SimMobility (*158*).



(a) Client entity (b) Vehicle entity

Figure 30 Life-cycle diagram of client and vehicle entity. Source: Zhang and Guhathakurta (*154*)

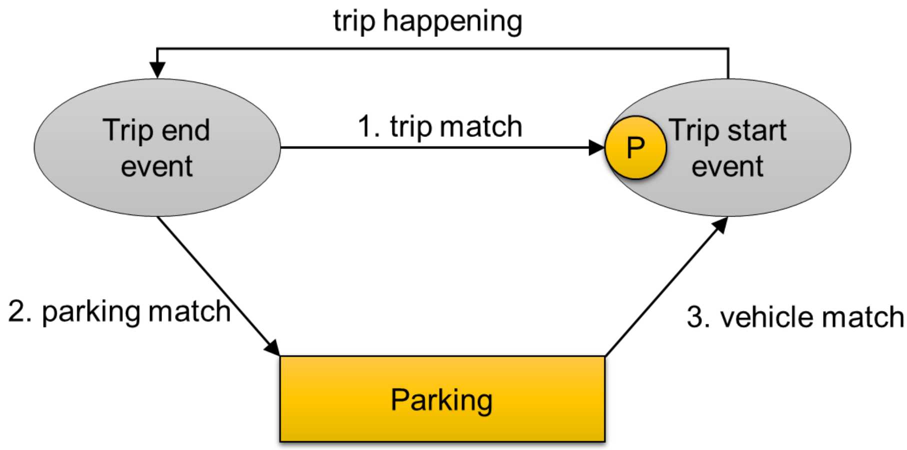


Figure 31 Matching processes used to assign vehicles to trips and parking to vehicles
Source: Kondor et al. (*134*)

Researchers uses scenarios that have proven to be accepted instrument for uncovering and structuring changes, their drivers, and consequences, in a partly unknown, uncertain, and rapidly changing environment. It is a useful tool for supporting long-term thinking and decision-making on transport and urban development policy. Such studies are always a simplification of reality since they cannot include all possible factors or developments that will occur (*159*). Such scenarios describe both a potential future situation and the development of the path leading from today into the future (*119*, *160*). Scenarios offer one possibility of drawing on conceivable future developments and their interrelations. For instance, existing literature presents one scenario system (see Table 11) where autonomous driving, as a feature of city of tomorrow is differentiated into three classification, regenerative/intelligent city, hypermobile city, and endless city (*119*, *161*). This table presents the overview and characteristics of scenario system mentioned earlier, based on form of autonomous driving, urban land use and driving factor. A qualitative review of future parking demand by KPMG (*162*) based on a set of three potential scenarios of AVs are: privately-owned; shared with single-occupancy; and shared with multiple occupancy is summarized in the Table 12.

Table 11 Overview of Scenarios in hypothetical driverless cities of tomorrow

Scenario	Form of autonomous driving	Urban land use	Driving factor
Regenerative city	-Flexible, multimodal, and networked public transport system as the backbone of urban mobility -Semi AVs (autopilot) on freeways	-Formation of intermodal mobility hubs -Reduction in land consumption for urban parking spaces due to new parking systems	-Technological development (in the energy system) -Conscious and responsible use of resources -Legislation and acceptance promotion by the state
Hypermobile city	-Highly networked (autonomous) mass taxi systems -AV on freeways with high transit volumes or along commuter routes, on reserved "guided lanes"	-City centers of high density -Growth of low-density suburbs	-Increasing acceptance of ICT due to its lifestyle and commercial benefits -Cooperation of state and private sector in developing the necessary ICT technologies
Endless city	-Predominantly vehicle-dominated -Low level of networking with public transport -No notable developments in automated driving	-Suburban growth -General decline of settlement densities	-Limited state power to steer development -Technological development restricted to efficiency gains in discrete areas

Table 12 The Impact of AVs on parking scenarios

Impact	Scenario 1	Scenario 2	Scenario 3
	Privately-owned	**Shared with single occupancy**	**Shared with multiple occupancy**
Number of vehicle parks	Equivalent to today, subject to whether vehicles can re-position themselves in different locations on the public road network	Lower than Scenario 1. Fewer vehicles require parking and duration of stay reduces.	Significantly lower than Scenario 1. Significantly fewer vehicles require parking.
Location	Basic autonomy will permit drop-off and parking, lots still need to be located near destination. Higher autonomy will allow drop-off at destination and parking located elsewhere	Vehicle parks could be in cheaper, out of town locations during periods of lower demand.	Vehicle parks located at key destinations with high demand to provide spare vehicles and servicing centers.
Parking revenues	Same as today or greater	Reduced due to less time spent in vehicle park and fewer parked vehicles.	Significantly reduced due to less time in vehicle park and significantly fewer parked vehicles.

Type of facility	Same as today. Opportunity to widen service offer		Vehicle parks transformed to become service centers and waiting areas until AV is requested by 'user'
Operational capacity	Capacity optimized (more vehicles, same space)	Fewer spaces needed than Scenario 1	Significantly fewer parking spaces needed than Scenario 1
Rate of change/ implementatio	Gradual implementation of AV floors (e.g., one floor at a time)	Rapid (i.e., once Uber decide to do this it will happen quickly)	Subject to local market conditions and familiarity with ridesharing

While some cities will gain significant benefits by introducing AVs, others might have to go for other mobility options, or worse, AVs might aggravate the problems that cities are hoping to solve (*128*). Papa and Ferreira (*163*) emphasized the prospect of significant technological, design-related, legal, and cultural changes that the AV technology could bring which would either improve or worsen accessibility in urban environments. They have also highlighted some critical views on the possible impact of AV on the land use and parking (see Table 13). Majority of the reviewed literature emphasized on scenarios in which AV impacts future parking behavior positively. The properties and potential uses of autonomous transport modes affect land-use and urban planning, influencing parking demand and organization, and the attractiveness of neighborhoods as places to live, shop or work (*119*). The changes that might follow depend largely on the direction in which autonomous driving evolves. The direction of shift will control net effect of AV on travel behavior and consequently must be incorporated in city planning to prepare for extreme future scenarios. The representatives and accuracy of the estimates from AV parking demand model entirely depends on the assumptions made in the analysis. Even though modelling assumptions frame and guide, directly or indirectly, the processes of argumentation, evidence generation, and conclusions, they are often discussed more critically in the limitations part of the research. A critical assessment of such assumptions used for various parking demand modelling and analysis, incorporating AV, presented in existing literatures and other sources is inevitable and forms the primary tasks in assessing their impact on parking and land use. The pessimistic views about future scenarios must also be modelled to anticipate covered and uncovered issues/impacts of AV on parking behavior and demand. Additionally, as autonomous vehicle technology matures, local zoning codes will need to address requirements for passenger loading and unloading, and when a shared use model is employed, parking needs will change drastically. Cities will need to determine how to make best use of the released land through new approaches to land use and zoning.

Table 13 Optimistic and pessimistic views about the impacts of AVs on land use and parking

	Optimistic Views	Pessimistic Views
Land Use	The quality of the built environment will be improved (re-centralization or regeneration of inner areas, re-densification, land use changes to new green public areas, residential locations). AVs are a way of promoting better quality of life in cities.	The built environment will be reshaped to accommodate the needs of AVs and their users in preference to the needs of other social groups. AVs increase suburbanization or sprawl due to the comfort of trips.
Parking	Parking policies will facilitate the conversion of redundant parking places into new recreational, green, and building areas, or into transport infrastructures for active modes of transport. Parking is limited within cities. Pick-up and drop-off spaces are only provided at a limited number of locations in the city.	Parking policies will remain as they are (AVs will use on-road parking spaces). A growth in AV ownership and use leads to an increase in demand for parking spaces in the city. Large numbers of pickup/drop-off points are created in the city which add to the amount of space allocated for vehicles.

Source: Stead & Vaddadi (*159*) , Adapted from: Papa and Ferreira (*163*)

Parking Recommendations

- Additional Structures and accommodations to support shared AVs to bring the maximum benefits to the system (see Figure 32) (*164*).
    - **Support facilities**: Large support facilities to service and charge AVs
    - **Staging areas**: AV fleets and shared-ride services need locations where they can idle when picking up or discharging passengers.
    - **Curb modifications for**:
        - parking with dynamic pricing
        - pickup/drop off during peak time
        - freight delivery at night
    - **Mobility hubs**: feeder service to public transport
- **Double Parking:** Large metropolitan cities can deploy double parking, a common way of parking vehicles where vehicles are parked next to another correctly parked vehicle within a stall or in the street, which temporarily increase the supply in locations where the city cannot offer better parking solutions during peak hours.
- **Parking lot shuttles**: Shuttles can be useful for remote parking. For example, DFW International Airport officials are considering a self-driving shuttle to ferry passengers around one of its remote parking lots with hopes of more AVs helping there in the future. The airport's board will consider a contract with EasyMile to lease a vehicle for six months to rove the remote parking lot, picking up passengers and bringing them to the front of the area where a human driver would then take them to terminals (*165*).

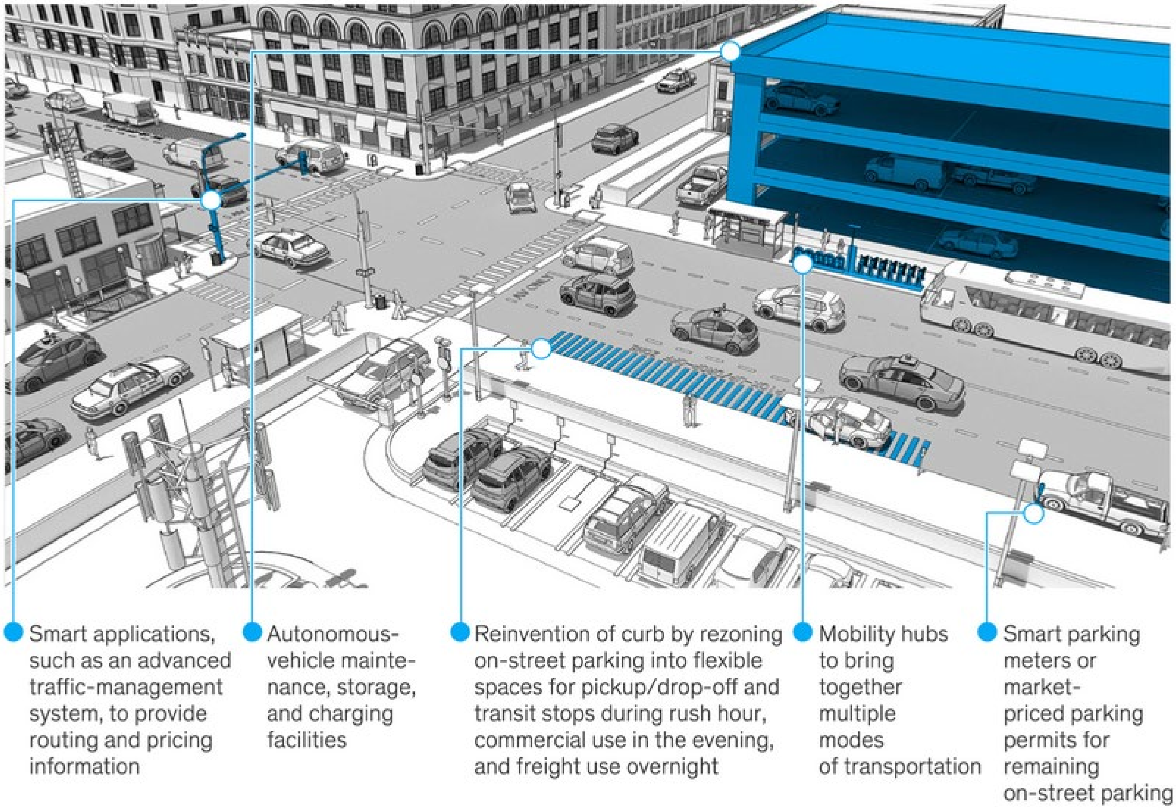


Figure 32 Structures and accommodations that may be needed to support shared AVs. Source: McKinsey & Company

- **Flexible facilities:** With increased use of ridesharing and the coming availability of AVs that might rarely need to park, lot operators may be able to convert existing facilities or design new ones in ways that enable multifunctional use or repurposing as a hedge against a future with less need for parking. The structural requirements of a parking garage (load-bearing needs, floor slopes, etc.) diverge in important ways from those needed for a retail or residential space, but some design firms are already planning for such convertibility. Parking structures with flat floors and higher floor to floor distances are recommended as these layouts allow for more flexibility and adaptability to a wider range of future potential uses (*166*, *167*) (see Figure 33).
- **Payments and pricing.** Seamless payments (potentially integrated with other transportation costs such as public transit passes or tolls) and dynamic pricing can provide opportunities for both public and private operators (*167*).

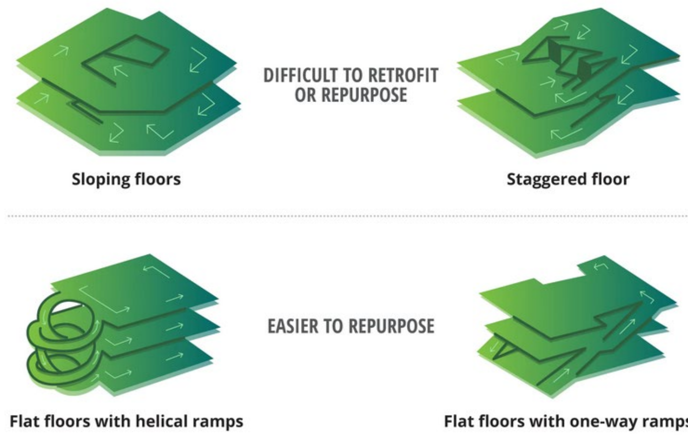


Figure 33 Retrofitting or Redesigning of existing vehicle park facilities. Source: Adapted from Gensler Research: The State of Parking: Our Progression Towards Automation

AUTOMATION IN FREIGHT SEGMENT

California based startup company named Nuro (see Figure 34), secured an AV deployment permit and is the first company to secure a commercial autonomous vehicle permit from California DMV (*168*). Unlike the autonomous testing licenses the California DMV previously granted to Nuro and others, which limited the compensation self-driving vehicle companies could receive, the deployment permit enables Nuro to make its technology commercially available. In Texas, the Global automated trucking company TuSimple is setting up shop at Alliance Texas' newly launched Mobility Innovation Zone, to establish new shipping routes to Austin and Houston for its automated trucks (*169*). The company already moves freight between Texas and Arizona. TuSimple already operates a facility in Texas, although it is dedicated to supporting UPS. The new center will be its first logistics hub in the state. TuSimple expects that it will begin removing humans from the equation in 2021, demonstrating fully driverless transportation on a limited number of routes. TuSimple plans to expand its routes in the next four years, starting with the addition of new delivery services throughout the Texas triangle in 2020 and 2021 (*170*).

Figure 34 Nuro's self-driving delivery units. Source: Engadget (*168*)

Truck transport is one of the key component in the freight industry, around 70% of the freight transport is handled by the truck industry (*171*). Moreover, it was determined that the truck industry will experience a shortage in drivers of 8 million by 2030 in European Union and the US (*172*). Further, driver operator costs were found to be a significant portion around 40% of the operating cost in a high-wage country like the US (*172*). Hence vehicle automation in the freight segment is being perceived as the solution for most of the existing problems. Since the number of benefits gained along with vehicle automation is perceived to be high for the trucking industry, it can be no surprise to note that freight organizations will be eager to see AVs on road. Several issues with CAVs are still unresolved, despite the potential benefits. Apart from operational concerns, doubts about legality, liability, security, privacy, and infrastructure must be addressed before CAVs can be fully adopted by the public. It is challenging to prepare for these problems unless policymakers and legislators know how quickly the public is likely to adopt CAVs. Therefore, faultless prediction of the market penetration of Autonomous Trucks (AT) is needed. A study has been performed to estimate the market share of ATs in Shelby County Tennessee (*173*). This study assumed various possible future scenarios from extremely disadvantageous situations to favorable situations and estimated the share of ATs using generalized bass models. The findings revealed that based on the maturity of technology over time, changes in pricing, and public opinion towards AVs, the market penetration could vary anywhere between 95 to 20% or less. Another study has examined the importance of peer's opinions in the trucking industry. Incorporating the factors from existing literature a discrete choice model was developed to reveal that large organizations are not affected much by the opinion of others whereas small organizations are highly influenced by the decisions taken by the large organization.

Another study employed a choice-based conjoint analysis to understand the preference of autonomous and alternate fuel vehicles in the truck sector(*174*). In addition, the truck sector values the driving range and charging time as the most significant attribute in adopting the new technology. Recently, with the outbreak of pandemic need for contactless delivery has increased and an important milestone has been achieved in the state of California(*168*). It is expected that with the introduction of AVs the most basic parameters that are going to change for autonomous trucks and Truck platoons are reaction time and speed. An interesting finding of this study was that the reaction time can drop to as low as 0.5 sec leading to a decrease in the reaction length by an enormous 75% (*175*). Further, it was recommended that with the introduction of Autonomous trucks the design speed limit could be reduced which can improve the reduction of speed differentials ultimately reducing the accident rates.

Moreover, truck automation can produce higher efficiency and safety gains giving rise to near term opportunities such as truck platooning and low-speed maneuvering (*176*). However few researchers observed that prolonged movement of trucks on a single path can be detrimental for pavement sustainability (*177*). Hence fatigue damage-oriented method was proposed to calculate the vehicle lateral position continuously based on the pavement load. Using this method, it was found that the fatigue damage reduced by 28% when trucks were 100% autonomous.

ELECTRIFICATION PROSPECTS

The role of how EVs fit into the CAV path is not clear yet. However, many researchers anticipate that when CAVs complete their market penetration and become another available model choice, they are most likely to be EVs. The operating costs of CAVs are expected to be lower due to the electrification and the potential for vehicle sharing. Vehicle travel has costs associated with purchasing or leasing, operating, and maintaining the vehicle. Travel decisions tend to focus on operating costs such as fueling and can be expressed in a model as a per-mile cost to capture higher costs for long-distance trips. Mobility operators such as Uber or Lyft see EVs as the vehicle options since they are less costly to maintain and operate. EVs also offer a more acceptable and easier means for rapid development and testing. EVs are generally cheaper to build, maintain and operate, so mobility services would have a natural preference for them. If such services could coordinate across an entire fleet, they could sidestep typical consumer concerns about EVs' battery range and charging station availability. That is because most taxi rides are well within current EVs ranges. Vehicles could be dispatched according to customer destination, battery life, recharging needs, and so on (see Figure 35).

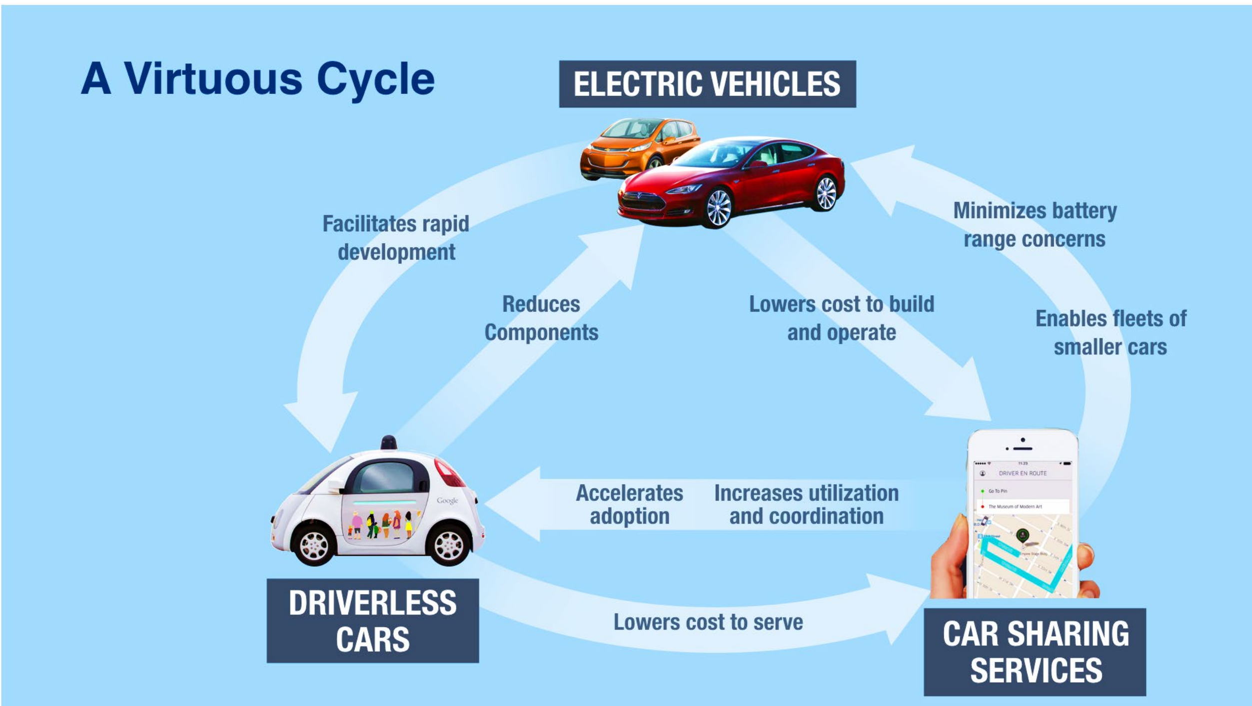


Figure 35 Electric vehicles and Autonomous future
Credit: Chunka Mui | Source: Medium (*178*)

CHAPTER 3 : REVIEW OF TEXAS ROAD DESIGN MANUAL

The objective of this chapter is to review current road design standards and analyze the advantages and disadvantages of various road design elements accommodating AVs and guide may be needed to these design standards to harness the maximum benefit from AV implementation.

This document is prepared in the same order as the chapters in the Texas Roadway Design Manual (RDM) such that a section is devoted to a chapter in RDM. Hence this document is organized as follows:

Section 2 deals with detailed discussion on the fundamental design criteria which determines the alignment, profile, and cross-section for roads and highways discussing the important design consideration for accommodating AVs and considering their distinct operational characteristics. Additional control criteria and considerations in accommodating AVs into the existing road infrastructure are discussed and tabulated in this section.
Section 3 proposes the changes that may be incorporated in the roadway projects which are newly designed and constructed or reconstructed. Similar to the Road Design Manual (RDM), classification of roadways is performed based on the functional class and modifications to accommodate AVs are proposed.
Section 4 proposes modifications on rehabilitation criteria for the pavement materials, capacity and conditions based on alignment, design speed and lane width of roadways. This section also describes safety guidelines for guardrails and headwalls specifications.
Section 5 discusses the restoration procedure of pavement, such as- change in turning lane, acceleration, and deceleration lane to ensure riding quality.
Section 6 involves special facilities where major modifications may be required. For example- Off-system bridge replacement and rehabilitation process, the Texas park and wildlife department facilitated areas and bicycle facilities.
Section 7 proposes the changes that may take place in the miscellaneous design elements. Miscellaneous design elements include the design elements which may not be a part of all highway projects. The current design standards of the RDM are studied and the probable modifications are recommended.
Section 8 Discusses mobility corridors with design speeds of 85 mph to 100 mph. Design elements regarding roadway design, roadside design, ramps, and direct connectors are discussed along with the proposed modifications.

It is important to note that this document aims at understanding the different design elements that could be impacted due to vehicle automation based on the existing literature. Since the vehicle automation technology is still in the early stages and is constantly evolving each day, the modifications proposed in this document do not necessarily indicate the ideal strategy/solution and can be enhanced over a period as technologies in AVs evolve.

Further suggestions provided in this memorandum was through consideration of SAE levels of autonomy. Further it has been considered that according to SAE for vehicles lower than level 2 human is responsible for Object Event Detection Response (OEDR) which ultimately describes that most of the design elements provided in RDM are still controlled by human drivers with vehicles only assisting drivers through ADAS. Therefore, the design guidelines are not expected to vary and should be the same as for human driven vehicles (HDVs) for vehicles lower than level 2.

For vehicles of SAE level 3 and above if a particular infrastructure element lies within the ODD of the level under consideration, then vehicle is assumed to take responsibility to maneuver along the segment without any disengagement. This is important to understand because, for example, if a SAE level 3 vehicle disengages in its ODD say due to machine failure or adverse weather conditions, and hands over the control to human, the controlling element would be human in that scenario. Therefore, any design changes suggested considering the enhanced capabilities of level 3 AVs would become obsolete. Therefore, it is necessary to remember that any modifications suggested in this document considering improved capabilities of vehicles that are higher than level 3 AV would only be applicable if there is zero disengagement. However, if a vehicle is assumed to disengage at any instance and performs DDT fallback leading to low-risk maneuver (or attaining minimal risk condition) that eventually leads human to drive off the vehicle then the suggested modifications would be obsolescent and design guidelines for conventional vehicles as provided in revised RDM still holds.

Section 2: Basic Design Criteria

The alignment of a highway or street produces a profound impact on the environment, the fabric of the community, and the highway user. The alignment consists of a variety of design elements that combine to create a facility that serves traffic safely and efficiently, consistent with the facility's intended function. Each alignment element should complement others to achieve a consistent, safe, and efficient design. Chapter 2 of the Texas RDM deals with the basic design criteria for road and highway design. The main elements are:

1. Functional Classifications
2. Traffic Characteristics
3. Sight Distance
4. Horizontal Alignment
5. Vertical Alignment
6. Cross Sectional Elements
7. Drainage Facility Placement
8. Roadways Intersecting Department Projects

This chapter deals with the discussion on the various fundamental geometric design elements that decide the alignment, profile, and cross-section for road and highway, and the existing design considerations for them. The impact of AV on these elements and additional design considerations required to incorporate AVs into the existing transportation network considering shared and AV dedicated infrastructure. Tables are included at the end of this chapter summarizing the results of this discussion (see Tables 4 and 5).

Functional Classification of Roads

Functional classification is the grouping of streets and highways into classes or systems according to the type of service they are intended to provide. Basic to this process is the recognition that most travel involves movement through a network of roads. Functional classification defines the role that any road or street plays in serving the flow of trips through an entire network.

The current levels of driving automation do not explicitly mention functional classes of road infrastructure. They are generally descriptive of the amount of automation and the relationship of the driver with the vehicle and thus describing the infrastructure at each level of vehicle automation that would optimize the safety and efficiency of the vehicles is a complex task. Roadway classification should clearly communicate roadway readiness for CVs and AVs. A classification system could also give drivers and passengers an understanding of their responsibilities on the roadways, removing the ambiguity that leads to the inappropriate assignment of driving tasks. It is also recommended that these classification standards be updated and revisited approximately every 5 years to recognize that technology (both vehicle and infrastructure) and research findings evolve over time. As CV AV technologies emerge, a classification system provides the framework for discussion between the automotive and roadway infrastructure industries. Such classification may also provide a means of externally verifying and enforcing vehicle compatibility with the comparable infrastructure of the roadway, particularly important concerning the ODD of such vehicles. Infrastructure classification may contribute to defining roadways where CVs and AVs can safely navigate based on the universal understanding of vehicle capabilities. Ultimately, redundancy between both vehicle and infrastructure is key to creating a safe and robust automated driving environment. Redundant systems need to be in place to function when the primary system fails. The greater the degree of automation in vehicles, the greater the need for redundant systems to protect both vehicles and passengers from malfunctions. A roadway classification system could further provide roadway infrastructure descriptions of the appropriate degree of redundancy to ensure a safe and robust driving environment. The Colorado Department of Transportation (CDOT) proposed a road classification system with six levels that relate to the roadway's ability to support CVs and AVs:

- **Level 1:** Unpaved and/or non-striped roads designed to a minimum standard level of safety and mobility.
- **Level 2:** Paved roads designed to American Association of State Highway and Transportation Officials (AASHTO's) guidance and pavement marking standards and signing designed to meet MUTCD standards. There is no ITS equipment or infrastructure to collect CV data. Access to cellular data service may be available.
- **Level 3:** ITS equipment operated by a Traffic Operation Center (TOC) and/or one-way electronic data share between DOT/vehicle/user and/or mixed-use lanes.
- **Level 4:** Roadway or specific lane(s) equipped with adaptive Intelligent transportation system (ITS) equipment (i.e., smart signals hold for vehicles, highway lighting that turns on for vehicles), with TOC override only and/or two-way data share between DOT/vehicle/user and/or lanes designated for vehicle Levels 3 and 4 only.
- **Level 5:** (Advance guideway system) roadway or specific lane(s) designed for vehicle Level 4 only, with additional features that may include inductive charging, advance/enhanced data sharing, and more. Additionally, no roadside signs are needed because all roadway information is directed to vehicles' on-board systems.
- **Level 6:** All lanes on a roadway designed for only vehicle Level 4 systems—no signs, signals, striping needed.

Traffic Characteristics

The selection of appropriate geometric features of a roadway is greatly influenced by the information about the traffic characteristics like traffic volume, traffic speed, and percentage of trucks or other large vehicles.

Traffic Volume

Traffic volume is an important basis for determining what improvements, if any, are required on a highway or street facility. Traffic volumes may be expressed in terms of average daily traffic (ADT) or design hourly volumes. These volumes may be used to calculate the service flow rate, which is typically used for evaluations of geometric design alternatives. Traffic volume and vehicle type influence the width and curvature of turning roadways and intersection corner radii.

Service flow rate is defined as a measure of the maximum flow rate under prevailing conditions. Service flow rate is the traffic parameter most used in capacity and level-of-service (LOS) evaluations which affect the selection of geometric design for an intersection, determining the appropriate type of facility and number of lanes warranted, performing ramp merge/diverge analysis, and performing weaving analysis and subsequent determination of weaving section lengths. Knowledge of highway capacity and LOS is essential to properly fit a planned highway or street to the requirements of traffic demand. The adjusting for prevailing conditions involves adjusting for variations in the factors like lane width, lateral clearances, free-flow speed, terrain, and distribution of vehicle type.

AVs act better than a human driver and are capable of sensing and foreseeing the lead vehicle's acceleration/deceleration decision and braking. They are expected to use the available space much better than an ordinary human driver. However, the extent of benefits is dependent on the proportion of the number of AVs against the number of ordinary vehicles, vehicle performances for instance the acceleration and deceleration rate, as well as the spacing between vehicles (*179*). The capacity effect is sensitive to market penetration. A single self-driving car can influence the traffic flow of at least 20 human-controlled automobiles around it. AVs, even with low penetration rates, can improve the stability of traffic flow on a highway by damping out the stop-and-go waves, though it may deteriorate the capacity of a freeway for mixed traffic scenarios (*180*). High-capacity values of up to 8500 vehicles an hour per lane can be achieved, if separate infrastructure is available and all vehicles using the lane can communicate with each other (*180*). With higher MPR of AV, significant changes in travel behavior can be expected at certain locations.

Speed

Speed is one of the principal factors considered by travelers in selecting alternative routes or transportation modes. The speed of vehicles on a road depends, in addition to the capabilities of the drivers and their vehicles, upon five general conditions: the physical characteristics of the roadway, the amount of roadside interference, the weather, the presence of other vehicles, and speed limitations (established either by law or by traffic control devices). Although any one of these factors may govern the actual travel speed. There are significant differences between design criteria applicable to low speed-45 mph and below and high speed-50 mph and above designs.

Design speed is a selected speed used to determine the various geometric design features of the roadway and during the selection, importance should be given to the attainment of the desired combination of safety, mobility, and efficiency within the constraints of environmental quality, economics, aesthetics, and social or political impacts.

Operating speed is the speed at which drivers are observed operating their vehicles during free-flow conditions. The 85th percentile of the distribution of observed speeds is the most frequently used measure of the operating speed associated with a particular location or geometric feature. The following geometric design and traffic demand features may have direct impacts on operating speed horizontal curve radius, grade, access density, median treatments, on-street parking, signal density, vehicular traffic volume, and pedestrian and bicycle activity. However, AVs will certainly narrow the spread of the distribution of speeds on alignments with a large penetration of AVs.

Posted speed refers to the maximum speed limit posted on a section of highway and represents the 85th percentile speed when adequate speed samples can be secured.

Running speed refers to the speed at which an individual vehicle travels over a highway section is known as its running speed. The average running speed on a given roadway varies during the day, depending primarily on the traffic volume. Peak and off-peak running speeds are used in design and operation.

Various Advanced Driver-Assistance Systems (ADAS) available to cars, including lane assist and adaptive cruise control, work well when driving in a limited ODD and there are no unexpected traffic events.

Speed Consideration for AVs

AVs will be programmed to not exceed the posted speed limit in an area. A platoon of closely spaced AVs that stops or slows down less, often resembles a train, enabling lower peak speeds, by improving fuel economy with higher effective speeds, improving travel time (*181*). While considering truck platooning, higher speeds may cause physical impacts to the roadway which will impact the design of pavement surface. For specific ODDs, dynamic speed limit that can be changed at any time, as based on the time of day, the prevailing traffic conditions, weather conditions, or any other external factors that causes ODD disengagements can be employed at a road section for safety reasons. For urban centers with high curb activities and pedestrian crossings, lower speed limits are proposed considering the safety of the curb users. For street designs with AVs, speed standards should consider priority road users by speed and use intensity for different road types (see Table 14).

Table 14 Prioritizing the street by type and zone

Street Type	Modal Priority	Shared Space
Urban (25 MPH)	Pedestrians > Bikes > Transit > Shared AVs > Single Occupancy AVs	Yes
Collector (30–50 MPH)	Bikes > Transit > Pedestrians > Shared AVs > Single Occupancy AVs	No
Urban Arterial (50+ MPH)	Transit > Bikes > Pedestrians > Shared AVs > Single Occupancy AVs	No
Neighborhood (<25 MPH)	Pedestrians > Bikes > Shared AVs > Single Occupancy AVs > Transit	Yes

Source: Riggs et al (*182*)

Safety

The safety analysis performed possibly should vary since the type of collisions that can happen with AVs are by far different from collisions arising due to humans. Therefore, the analysis required should be quite different that needs further research to derive suitable inferences.

Sight Distance

The arrangement of geometric elements to provide adequate sight distance for safe and efficient traffic operations during different light, atmospheric conditions, and drivers' visual acuity, is one of the fundamental road design inputs. Required sight distance is the length of the roadway ahead that is visible to the driver in order for the driver to make safe driving decisions such as coming to a full stop. The available sight distance on a roadway should be sufficiently long to enable a vehicle traveling at or near the design speed to stop before reaching a stationary object in its path. The sight distance at every point along a roadway should be at least that needed for a below-average driver or vehicle to stop. Design criteria for SSD vary with vehicle speed. The sight distance available on downgrades is larger than on upgrades, automatically providing the necessary corrections for grades, to account for gravitational dynamics affecting the braking of vehicles on grades. Multilane roadways should have continuously adequate stopping sight distance, with greater than design sight distances preferred. Sight distance records for two-lane highways may be used effectively to tentatively determine the marking of no-passing zones in accordance with criteria given in the Texas Manual on Uniform Traffic Control Devices (TMUTCD). The recommended SSDs are based on passenger car operation and do not explicitly consider design for truck operation. Trucks, especially the larger and heavier units, need longer stopping distances for a given speed than passenger vehicles, however, these longer stopping distances are balanced by the advantage point of view of the truck driver that is higher than for passenger cars. The four aspects of the sight distance are: **Stopping Sight Distance (SSD):** Stopping sight distance is the sum of the distance traveled during perception and reaction time and the distance to stop the vehicle. For autonomous vehicles that are level 3 and above, the reaction time required is usually less than human drivers therefore such vehicles can have shorter reaction time when the technology is at high levels of maturity. In few instances the same applies for level 1 and level 2 vehicles using ACC especially in the circumstances when the leading vehicle applies hard brakes. However, for level 1 and level 2 vehicles driver is responsible for OEDR, therefore as long as vehicles that are lower than level 2 exist on road it is imperative that design guidelines of HDVs for stopping sight distance should still hold. **Decision Sight Distance (DSD):** Decision sight distance has been defined as the distance at which drivers can detect a hazard or a signal in a cluttered roadway environment, recognize it or its potential threat, select an appropriate speed and path, and perform the required action safely and efficiently. Because decision sight distance provides drivers additional margin for error and affords them sufficient length to maneuver their vehicles at the same or reduced speed rather than to just stop, its values are substantially greater than stopping sight distance. Recommended sight distance values in Table 2-2 of RDM may still hold for any level of autonomous vehicles. Since at this stage it is still unclear on how accurate the technology is able to predict surroundings, it is recommended to maintain conservative values as given in Table 2-2 of RDM. **Passing Sight Distance (PSD):** Passing Sight Distance is the minimum sight distance that is required on a highway, generally a two-lane, two-directional one, that will allow a driver to pass another vehicle without colliding with a vehicle in the opposing lane. This distance also allows the driver to abort the passing maneuver if desired. Certain two-lane highways should also have sufficient sight distance to enable drivers to use the opposing traffic lane for passing other vehicles without interfering with oncoming vehicles. Two-lane rural highways should generally provide such passing sight distance at frequent intervals and for substantial portions of their length. Providing passing sight distance on two-lane urban streets or arterials has low priority. **Intersection Sight Distance (ISD):** Intersection sight distance is typically defined as the distance a motorist can see approaching vehicles before their line of sight is blocked by an obstruction near the intersection. Although the AVs have lidars, cameras that aid in detecting the surrounding vehicles. Machine vision cannot penetrate through the buildings and other roadside structures to identify vehicles, bikes, and pedestrians, therefore at urban intersections the sight triangles are similar for AVs and HDVs. Yet it is noteworthy to highlight that the AVs do have longer ranges that can be taken advantage of in intersections that do not have any occlusions blocking the machine vision. Regardless, the sight triangle for AVs is wider than HDVs. However, similar to SSD, intersection sight distance is not expected to vary as long as vehicles lower than level 2 exist on road.

Horizontal Alignment

Horizontal alignment is necessary for gradual change in direction when a direct point of intersection is not feasible especially at highways, interstates, high speed roads with a constant flow of traffic, etc. Several general considerations are important in attaining safe, smooth flowing, and aesthetically pleasing facilities. The two basic elements of horizontal curves are curve radius and, superelevation rate. Design speed is used as the overall design control. The design of roadway curves should be based on an appropriate relationship between design speed and curvature and their joint relationships with superelevation and side friction. Superelevation is defined as the tilting of the roadway to help offset centripetal forces developed as the vehicle goes around a curve. Along with friction, they are what keeps a vehicle from going off the road and must be done gradually over a distance without a noticeable reduction in speed or safety. The minimum radii of curves are important control values in designing for safe operation. High rates of superelevation create steering problems for drivers traveling at lower speeds, particularly during ice or snow conditions. Further various challenges on adopting sharp curves are discussed in section “General Considerations for Horizontal Alignment” of RDM. Compared to HDVs, AVs can take sharper turns since the defined waypoints make it possible to have tight maneuvers. However, these maneuvers are limited by the comfort of passengers in vehicles and toppling effects. Therefore, further research is essential to quantify the number of improvements that can be achieved under autonomous vehicles. More importantly, the aforementioned changes should be applicable only when there is 100 percent penetration of AVs that are greater than level 3. Further the maximum deflection angle is not expected to vary in a mixed traffic environment therefore current guidelines are still applicable.

Super Elevation Transition Length

Since the main controlling factor in determining transition length is the comfort and safety of passengers, design guidelines are not expected to vary for mixed as well as complete autonomous future. However, the adjustment factors for multilane facilities provided in table 2-7 in RDM may require further attention for complete autonomous future since those values were derived considering HDVs. Super elevation transition type and placement is not expected to differ significantly in mixed traffic environment, current design guidelines still hold.

Sight Distance on Horizontal Curves

SSD dictates the sight distance on a horizontal curve, which as discussed in earlier sections is not expected to vary in mixed environment. Therefore, the guidelines as given in updated RDM still holds. Further it is important to mention that under complex geometries that cause sight obstructions, some alternative measures to alleviate the situation are discussed in updated RDM. Among them one alternative is to provide wider shoulders. Wider shoulder can provide additional benefit for level 3 and 4 AVs and can be considered as a suitable alternative if there is high market penetration of AVs since it can also allow for handling disengagements. However, as mentioned in revised RDM shoulder wider than 12 ft is not recommended since human drivers may use it as a travel lane violating the norm.

Existing Design Consideration

Perception Reaction Time (PRT): Brake reaction time of 2.5 s is considered adequate for conditions that are more complex than the simple conditions used in laboratory and road tests, but it is not adequate for the most complex conditions encountered in actual driving.

Deceleration Rate: A deceleration rate of 11.2 ft/sec² is also considered to be comfortable for 90% of drivers and is easily attainable with properly maintained pavement skid resistance. The SSD and the DSD models are directly based on the driver's perception reaction time or PRT, in addition to the braking distance. They are key elements in designing vertical and horizontal alignments and locating highway signs. The driver's eye height and the degree of illumination of the headlight beam are also key elements in designing crest and sag vertical curves, respectively (*183*).

Height of Driver's Eye: For passenger vehicles, the height of the driver's eye is 3.50 ft above the road surface. For large trucks, the driver eye height ranges from 3.50 to 7.90 ft. The recommended value of truck driver eye height for design is 7.60 ft above the road surface. For night driving, the vehicle headlights provide visibility and thus the height of the headlight from the ground surface will have an impact on the available sight distance, especially at places where there is no artificial illumination of the road surface. The height of headlights should be mounted not more than 54 inches in height and not any lower than 22 inches, above the surface.

Height of Object: For stopping sight distance and decision sight distance calculations, the height of the object is 2.00 ft above the road surface; for passing sight distance calculations, the height of the object is 3.50 ft above the road surface.

Sight Distance Consideration for AV

The existing infrastructure design and operational criteria were established to meet the needs of human drivers which may not be optimal for AVs and does not consider possible advantages in detection of road hazards associated with AV sensors. SSD is directly based on drivers' PRT, in addition to the braking distance. Existing literature states that human reaction times are larger in comparison to those of AVs. Extensive machine simulation and computation showed that the reaction time of autonomous vehicles is in the order of 0.2- 0.5 seconds (*183*). Reaction-time of 0.5 seconds can be used for level 4 automation and 0.2 for fully AVs (*184*). Future vehicles can achieve higher coefficients of road friction and improvements in powertrain and braking technologies leading to considerable improvements in the acceleration and deceleration rates for even low-cost vehicles, benefiting non-AV vehicles also. However, acceleration and deceleration rates used for roadway design will always need to consider limits in human tolerance to such rates. The deceleration rate of an AV could be greater than that adopted by AASHTO for human-driven vehicles, 11.2 ft/sec². Recalculation of SSD with new reaction time and deceleration rate shows a significant reduction, which directly impacts other geometric design criteria such as horizontal alignment, vertical alignment, etc. Reconfiguration of road design attributes dealing with the alignment, profile, and cross-section based on new SSD values for AV dedicated roads, could be possible but associated with large construction costs. The posted speed limit could be regulated at critical locations to ensure smooth and safe movement of both types of vehicles at the initial stages. More research is needed to gauge the passing maneuvers for AVs, especially in a mixed traffic scenario, where the road system is shared by both types of vehicles. The frequency and length of passing sections need to be assessed especially for scenarios where AV shares lanes with human-driven cars, considering their automated speed on specific ODD. In adverse weather conditions, the visibility and sensing capabilities of AVs may be impacted and may require higher values of SSD.

Camera Vs LiDAR

AVs have video cameras and sensors to see and interpret the objects in the road just like human drivers do with their eyes. Existing technology allows AVs to monitor maintaining the 360° view of their external environment, thereby providing a broader picture of the traffic conditions around them. There is an ongoing debate among self-driving car industry experts on whether LiDAR (Light Detection and Ranging) or cameras are the most suitable for SAE Level 4 and Level 5 driving. LiDAR's technology has been extensively tested and deployed by company's like Waymo, Cruise, Velodyne etc, (*185–187*). The cameras on Tesla models are used by its Autopilot self-driving feature to provide a 360-degree view of its surrounding(*188*, *189*). Currently, all of Tesla's vehicles have a forward-facing radar hidden at the front of the car, providing a long-range view of distant objects. Tesla insists computer vision, supported by cameras and radar is will be the future (*189*, *190*). Fully self-driving cars have such hybrid camera-sensor based monitoring system. The way these sensors/cameras are attached on AVs and how they monitor will have direct impact on the sight distance and consequently other geometric elements impacted by it.

Automated Speed

Existing research has shown the significance of automated speed and horizontal curvature. Automated speed is the maximum speed that a certain driving automation system can attain along a certain geometric layout. Automated speed was found to be lower than design and operating speeds for sharp-to-medium curves (*191*). Reassessment of posted speeds on such road segments will be required and monitored frequently with the higher market penetration levels of AVs. Additionally, it is extremely important to keep track of the technological developments in sensor technology, digital infrastructure, and ODD information of different AVs.

Fallback Ready User

There exists a small-time gap between an ODD exit/ failure and achieving a minimal risk condition that may involve a fallback-ready user to take control of the AV. "A level 3 ADS experiences a DDT performance-relevant system failure in one of its radar sensors, which prevents it from reliably detecting objects in the vehicle's pathway. The ADS responds by issuing a request to intervene to the DDT fallback-ready user. The ADS continues to perform the DDT, while reducing vehicle speed, for several seconds to allow time for the DDT fallback-ready user to resume operation of the vehicle in an orderly manner."

For level 4 AVs, either driver takes back driving tasks, or the system achieves a minimal risk condition traveling at a lower speed. Further research may be needed to understand the time needed for safe user takeback of driving task and capability of the user to conduct takeback under ODD exit or system failure, which may become important for designing roadway elements.

Communication and Connectivity

Vehicles with AV technology will benefit from communicating with the roadway infrastructure and users of the transportation network rather than just relying on on-board sensors and a static starting map to understand the conditions of the roadway. Similarly, CVs without automation technology may provide drivers with alerts about upcoming roadway conditions, like blind spot warnings, but adding automation will more effectively eliminate potential human error (*192*). Even in the absence of vehicle automation, data connectivity in transportation systems promises a myriad of benefits for travelers and society. V2I communication will lead to less time-consuming and more ecologically friendly driving. Vehicle-to-everything (V2X) wireless communication technologies have been introduced to allow vehicles to share information within and beyond the line of sight, with each other and with the fixed infrastructure. V2X connectivity can enhance the capability of AVs to perceive their environment. Connected AVs can see around a blind corner when moving toward an intersection and know whether any vehicle is approaching from other directions (*193*). Ge et al. (*194*) experimentally showed that a single connected AV (CAVs) utilizing beyond-line-of-sight information appropriately may improve human-dominated traffic flow while being an integral part of the flow.

For cases where AV shares lanes with conventional drivers, due to the presence of human driving factors in the roadway, conventional values of SSD are to be followed. For dedicated/special AV lanes, SSD could be reduced due to the improved reaction time and smoother vehicle dynamics of AVs when an obstacle is encountered. Under mixed traffic, the length and rate of the grades must be limited to as low as possible to avoid undesirable speed differentials. For AV dedicated lanes, the speed differentials can be kept under control. Hence, steeper grades can be achieved. However, grade design should be dominated by the ability of the design vehicle to climb the slopes and comfort of the passenger on-board. As the curve radii depend upon the superelevation rate and side friction factor as well as the design vehicle dimensions, no modifications are expected. However, a larger radius should be provided whenever enough right of way (ROW) is available.

Vertical Alignment

Vertical alignment is controlled mainly by topography and structure clearances, but the factors of horizontal alignment, safety, sight distance, design speed, construction costs, and the performance of heavy vehicles on a grade also must be considered. The two basic elements of vertical alignment are grades and vertical curves. Vertical curves are designed for the vehicle to travel smoothly from one tangent grade to another tangent grade. The selection of vertical alignment should be predicated to a large extent upon the following criteria:

- Obtaining maximum sight distances,
- Limiting speed differences (particularly for trucks and buses) by reducing the magnitude and length of grades,
- A latent dip that would not be apparent to the driver must be avoided,
- Steep grades and sharp crest vertical curves should be avoided at or near intersections,
- Flat grades and long gentle vertical curves should be used whenever possible.

Vertical curves are designed parabolic in shape and classified as a crest vertical curve and a sag vertical curve.

Crest Vertical Curve: The crest vertical curve length is determined using minimum SSD criteria and is suitable from the safety and aesthetic aspect. There are two cases to determine the minimum length of crest vertical curves based upon whether the minimum stopping sight distance required is greater than or less than the length of the curve. However, the current version of the "Green Book" recommends a single mathematical approach for the minimum length of crest vertical curves.

Sag Vertical Curve: The length of the sag vertical curve necessary depends upon four different criteria like headlight sight distance, comfort for the passenger, drainage aspect, and aesthetics. Normally, the headlight sight distance along with rider comfort criteria is adopted to find the length of the sag vertical curve.

As stated in updated RDM, length of grades is usually reliant on the operational characteristics of trucks rather than passenger cars, therefore steep gradients may yield high speed differentials that may hinder the stability of traffic flow. Though higher acceleration/decelerations rates of AVs and better SSD can alter the vertical alignment design at higher penetration of level 3 and above AVs, factors such as passengers' comfort, drainage control might still impede the implementation which warrants further research. However, in case of mixed traffic environment HDVs still regulate the design and no changes are expected in the vertical alignment designs.

Vertical Alignment at Railroad Crossings

The controlling factors in this case is sight distance, rideability and breaking /accelerating distances. Fortunately, the AVs have much better sight distance and braking or accelerating distances which provide us the scope to have more steeper gradients if the rideability is not affected significantly. These changes are not expected to take place if vehicles lower than level 2 share the common space.

Cross- Sectional Elements

The major cross section elements considered in the design of streets and highways include cross slope, lane widths, shoulders, roadside or border, curbs, sidewalks, driveways, and medians.

Lane Width

According to RDM the minimum width on freeways and majority of rural arterials is 12 ft. Urban roads with low speeds adopting 11 ft or 12 ft is the general practice.

Autonomous driving presents opportunities for narrower traffic lanes, but to accommodate trucks and buses, large reductions are only feasible on special lanes limited to car traffic. As autonomous vehicles become more common, governments will be asked to dedicate highway lanes to their use, to allow platooning. Similarly, autonomous vehicles could eliminate the need for traffic signals, but this is only feasible in areas where all vehicle traffic is autonomous and connected. Lane width on horizontal curves for AV, depending on the automated speed, may require modifications considering ODD disengagements. Lanes without full-size passenger buses or trucks can have reduced width and the captured space can be repurposed for designing safer pedestrian/bike friendly streets and promote curbside activities. Reduced lane widths increase the safety of pedestrians crossing the road. Accommodating pedestrians and bicyclists is a critical social issue for street design, but not for uninterrupted freeways traffic.

One of the anticipated impacts of AV is increased freeway capacity. Multiple literature in the past has highlighted narrower lanes to improve efficiency and reduce cost (narrower lanes means less pavement (e.g., asphalt or concrete materials), less runoff, and less right of way) without impacting safety. Further research on the feasibility and safety of using narrower lanes with AVs is recommended. Additionally, AV presents an opportunity for road dieting/ safe retrofitting of existing design to incorporate dedicated infrastructure with communication module to provide connectivity. The evolution of sensing technology to detect road environment (pedestrian/bicyclists etc.) will impact the street design. A study conducted in Spain (*195*) , found the following impact of reduced road width on Level 2 semi-AV on urban arterial:

- semi-autonomous system tended to fail on narrow lanes.
- There was a maximum width below which human control was always required referred to as the human lane width measuring 8.20 ft.
- a minimum width above which automatic control was always possible the automatic lane width was established to be 9.02 ft
- a lane width of 8.92 ft was found to have the same probability of automatic and human lateral control, namely the critical lane width.

Curbs

Curbs are used primarily on frontage roads, crossroads, and low-speed streets in urban areas. The type and location of curbs affect driver behavior and, in turn, the safety and utility of a highway. Curbs serve any or all the following purposes: drainage control, roadway edge delineation, ROW reduction, aesthetics, delineation of pedestrian walkways, reduction of maintenance operations, and assistance in orderly roadside development. A curb, by definition, incorporates some raised or vertical element. Vertical curbs are defined as those having a vertical or nearly vertical traffic face 6 inches or higher. Vertical curbs are intended to discourage motorists from deliberately leaving the roadway. Sloping curbs are defined as those having a sloping traffic face 6 inches or less in height. Sloping curbs can be readily traversed by a motorist when necessary. A preferable height for sloping curbs at some locations maybe 4 inches or less because higher curbs may drag the underside of some vehicles. Curbs should not be used in connection with the through, high-speed traffic lanes or ramp areas except at the outer edge of the shoulder where needed for drainage, in which case they should be of the sloping type.

The impact of AVs on curbside activities has been well addressed in the existing literature, with emphasis on urban streets. AVs can travel closer together than human-operated cars, creating space for more cars within existing lanes opening the road for alternative forms of transportation, such as trams/streetcars, bus lanes, bikes, and scooters. An important observation that needs to be made is that for all levels of AVs having a solid line next to curb is essential to avoid overturning of vehicles. In the absence of proper markings AVs fail to detect the presence of curbs that can compromise the safety of AVs. It is particularly helpful to detect the presence of low-profile obstacles unless machine vision and sensing technology improves to detect them. As significant numbers of people switch from auto ownership to a shared model, demand for pick-up and drop-off along streets will grow. Driveways may be replaced with landscaping or buildings enhancing the experience of pedestrians, joggers, and bicyclists as they have fewer driveways to cross. Pedestrian and cycling-based infrastructure need to be given similar or equal investment alongside AV infrastructure in the street redesign. The potential impact of future mobility as a service model on curbside dynamics for various users has been presented in Table 15. Existing curbside needs to be redesigned, considering ODD of AVs, nearby land use, parking demand distribution, etc.

Table 15 Potential changing dynamics of curb use demand

User Group		Uses of the Curb	Motivations	Predicted Changes in Curb Use
Travelers	Drivers	Parking Pick-up and drop-off	Convenient access	Parking – reduction in availability and legitimacy of on-street parking if move to pick up and drop off
	Cyclists	Travel largely adjacent to the curb and sometimes on facilities adjacent to or part of the sidewalk. Use also for parking bikes at formal or informal points	Safe and well-maintained cycle paths or sides of road with adequate space. Secure and convenient parking spaces with low risks of theft.	Access – growth in cycle paths
	Pedestrians	Moving between destinations, health (e.g., jogging, dog walking), crossing roads, browsing, socializing,	Varied but requires consideration of diversity with safety (e.g., lighting) and disabled access important	Unlikely to change but may be more concentrated in some locations
	Public Transport Users	Pick up and drop off at fixed points	Convenience Accessibility	Pick up and drop off – more likely to be flexible rather than fixed with growth in Mobility as a Service
Transport Providers	Emergency Services	Access to adjacent land uses	Convenience Accessibility	Unchanged with exception of implications of curbside congestion
	Taxi Companies	Principal point of transaction with passengers both at formal stands and in hail and ride situations.	Ability to stop and drop off or collect passengers wherever required and minimal delays to journeys	Reduction in formal fixed stands as result of rideshare

			resulting from other curb use. Formal stands in commercially sensible locations.	
	Bus Companies	Principal point of transaction with passengers through a series of formal bus stops	Ability to stop without being delayed when rejoining traffic stream. High quality waiting facilities at curbside to encourage bus use and step free boarding facilities	Pick up and drop off spaces – required to be more flexibly located with rise of on-demand services and automation
	Bike Share Companies	Bikes are made available on the curb adjacent to popular land-uses and public transport interchanges. Can be dynamic	Maximizing use of asset, sometimes advertising	Bikes are made available on the curb adjacent to popular land-uses and public transport interchanges. Can be dynamic
	Car Share Companies	Exclusive access for pick up and drop off	Cheap parking	Require dedicated parking 'pods' as car sharers pick up/drop off cars
	Ride Share Companies			Increase in pick up and drop off activity, increasing regulatory and political influence
	Electric charging operators	Parking and charging of EVs/PHEVs	Cheap parking and charging	Dedicated access for EV charging and requiring dynamic management
Adjacent Land Use	Residents	Main point of access to property is from the curb and this may also be a place where own vehicles are parked depending on development type	Protecting amenity of property and ensuring easy access to vehicles where	Dedicated driveway as main point of access to property likely to decline; give way to pick up/drop off access

			owned, particularly for those with disability	
	Shops/ Bars/ Restaurants	Main point of access to property is from the curb. Shop may spill on to curb or be a kiosk on the curb. Require access for deliveries.	Maximizing footfall and expenditure to the shop, often considered to be supported by available parking for shoppers	Main point of access to property is from the curb. Shop may spill on to curb or be a kiosk on the curb. Require access for deliveries.
	Hotels	Main point of access is from the curb. Seating and patrons may spill on to curb. Require access for deliveries.	Convenient access to facilitate easy luggage transfer and sometimes for privacy or comfort of guests	May strongly assert privacy of road space
Street Services	Refuse operators	Main point of access is from the curb. Larger hotels often have private forecourt for pick up and drop off as premium feature	Minimizing distances which refuse needs to be carried from bin to vehicle	Temporary stopping at curbside to allow collection of refuse
	Delivery companies	Parking at curbside to allow primary distribution/collection function	Most convenient access to end delivery sites and minimized time of search for space	Increase in quantity of delivery; increase in economic importance and political influence

Adapted from Marsdon et al. (*196*)

Shoulder Widths and Clear Zone

Shoulders are of considerable value on high-speed facilities such as freeways and rural highways. Shoulders, in addition to serving as emergency parking areas, lend lateral support to the travel lane pavement structure, provide a maneuvering area, increase sight distance of horizontal curves, and give drivers a sense of safe, open roadway. Shoulders are not intended for use by through traffic, although there are exceptions. Shoulder widths should accommodate bicyclists where a designated bicycle lane or shared use path is not provided. On urban collectors and local streets, parking lanes may be provided instead of shoulders. On arterial streets, parking lanes decrease capacity and are discouraged. In the absence of higher-level AVs (specifically higher than level 3 AVs), as mentioned in the RDM, the purpose of shoulders on freeways or multilane rural highways is to provide space for stopped vehicles with other benefits such as increase in sight distance and emergency parking's. However, when AVs higher than level 3 start utilizing the space since these vehicles are programmed to come to rest while disengaging, it is highly recommended to increase the width of shoulders to facilitate safe place for disengagement. However, such alterations should be a function of market penetration of AVs to optimize infrastructure investment.

A clear zone is the unobstructed, traversable area provided beyond the edge of the through traveled way for the recovery of errant vehicles. The clear zone includes shoulders, bicycle lanes, and auxiliary lanes, except those auxiliary lanes that function like through lanes. Such a recovery area should be clear of unyielding objects where practical or shielded by crash cushions or barriers. The design of clear zones should also consider errant vehicle performance and slope maintainability. In regard to highways, the modifications suggested to the shoulders was to increase the shoulders width. It is noted that Clear Zone guidance will be updated per the release of the new AASHTO Roadside Design Guide.

Median

A median is provided primarily to separate opposing traffic streams and the design width dependent on the type and location of the highway or street facility. In rural areas, median sections are normally wider than in urban areas. Wherever the right-of-way costs are prohibitive, reduced median widths may be appropriate for certain rural freeways. For cases where AV shares the road with conventional drivers, median barriers can be provided as per existing design criteria. AV traffic can stay in their direction of flow due to various ADAS capabilities. Instead of median barriers, flush medians can be provided to reduce cost and improve traffic throughput. On the contrary, many incidents that require physical separation with barriers are single vehicle crashes because of tire blow up or hydroplaning. AVs are not immune to that.

Cross-Slope

The operating characteristics of vehicles on crowned pavements cross slopes up to 2 percent. For uncurbed pavements, A steep lateral slope is desirable to minimize water ponding on flat sections. With curbed pavements, a steep cross slope is desirable to contain the flow of water adjacent to the curb, especially in areas of high rainfall. Pavement cross slopes on all roadways, exclusive of superelevation transition sections, should not be less than 1 percent. Special care should be given to pavement cross slope as stagnation of water in the pavement may lead to the unstable performance of AVs.

Slopes and Ditches

Side slopes refer to the slopes of areas adjacent to the shoulder and located between the shoulder and the right-of-way line. For safety reasons, it is desirable to design flat areas adjacent to the travel-way, so that out-of-control vehicles are less likely to overturn, vault, or impact the side of a drainage channel. The side slopes provided should be as flat as possible to aid the out-of-control vehicle to recover or make a controlled deceleration. The existing recommended values may be followed under mixed traffic as well as dedicated AV lanes.

Lateral Offset to Obstructions

Lateral offsets are the uniform clearance between traffic and roadside features such as bridge railings, parapets, retaining walls, and roadside barriers. The lateral offset to obstructions helps to avoid impacts on vehicle lane position and encroachments into opposing or adjacent lanes, improve driveway and horizontal sight distances, reduce the travel lane encroachments from occasional parked and disabled vehicles, improve travel lane capacity, and minimize contact from vehicle-mounted intrusions (e.g., large mirrors, car doors, and the over-hang of turning trucks). The existing recommended values may be followed under mixed traffic as well as dedicated AV lanes.

Pavement Taper Lengths

Length of pavement tapers are not greatly affected by the presence of AVs since it is a characteristic of the speed of section under consideration. However, the approach in which tapering of a section is done is extremely important for AVs. Most importantly the approach taken should be uniform or standardized for the vehicle to perceive. For example, tapering due to obstruction should be standardized to have continuous pavement markings for the vehicle to recognize its surroundings.

Drainage Facility Placement

Drainage becomes a significant design control factor while dealing with AVs. Waterlogging/ heavy rainfall/ snow can reduce the ability of AV to sense the environment, cause the automation system to fail in their ODD. Exceptional care should be given to pavement cross slope as stagnation of water in the pavement may lead to the unstable performance of AVs. For both the mixed traffic and AV dedicated lane, the cross slope should be inclined in the same direction as the main lanes of the roadways. Cross slope provided will be dependent on the pavement used and drainage considerations. Tables 16 and 17 summarizes basic design criteria and design considerations for AV.

Table 16 Basic design criteria and design considerations for AV- part 1

Design Element	Influencing Factors	Existing Consideration	Implication to CV AV on geometric design
Functional Classification	Accessibility Mobility	Service function Traffic Volume Flow Characteristics Speed	• Existing Functional Classifications remains same • Additional Connected Roadway Classification System Development (CRCS)- based on CV AV readiness: ○ useful to state and local departments of transportation and metropolitan ○ Help in plan appropriate design components for each type of facility ○ Enables clear communication
Traffic Characteristics	Traffic Volume	Average Daily Traffic Design Hourly Volume Directional Distribution during Design Hour Directional Distribution K Factors Service Flow Rate	○ Autonomous vehicles may significantly decrease the disutility, or travel time costs, associated with driving a vehicle ○ Offer greater potential to result in more stable traffic flows, could potentially increase roadway capacity by creating shorter headways, less weaving, and more predictable and coordinated movements, particularly on freeways and expressways ○ Travel behavior changes on trip making * Impact will be more prominent at higher MPRs, and requires revision of traffic characteristics at AV dominated locations/infrastructure ○ Generate additional VMT from empty trips (zero-occupancy trips)

	Design Speed	○ Operating speed ○ Topography ○ Adjacent land use, ○ Modal mix ○ Functional classification of the roadway	○ Design speed for shared infrastructure can be same ○ Design speed can be optimized for dedicated or special facilities for AVs - impact another geometric element ○ Automated speed of AVs on ODD should be considered for posted speed.
	Terrain	Refer Chapter 2, section 2 (page 2-7) for information on safety	Terrain remains the same for AV
	Safety	Refer Chapter 2, section 2 (page 2-7) for information on safety	New principles of safety analysis may be required for AV involved incidents - separate consideration may be required for within ODD incidents and disengagements incidents
Sight Distance	○ Vehicle Speed ○ Driver's total reaction time ○ Characteristics and conditions of the vehicle ○ Friction capabilities between the tires and the roadway surface ○ At night, sight distance dependent on the position of the headlights and the direction of the light beam	Stopping Sight Distance: Speed, PRT Decision Sight Distance: Speed, PRT, Maneuver type Passing Sight Distance: (discussed in chapter 3 and 4) Intersection Sight Distance: Refer chapter 2, section 3, page 2-13 for general consideration factors Sight Distance at Under-Crossing: length of vertical curve, vertical clearance, eye height, object height	○ Road monitoring task is done by sensors, within ODD - Improved reaction time (improves with technology) - height of driver will be replaced by sensor height ○ Adjusting vehicle speed more predictively through vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communications to avoid sharp braking ○ Need to consider the automated speed on ODD ○ Provision of communication infrastructure at specific ODD range further improve sight distance and consequently other design elements dependent on sight distance - railway crossings/bridge structures/ intersections etc., ○ Artificial illumination required wherever necessary, high priority - Utilizing Internet of Things (IoT) technology, streetlights can communicate with AVs about upcoming traffic patterns, relay crash avoidance data, or guide them to use a preferred route. ○ Frequency and length of passing sections needs to be assessed for shared lanes

Horizontal Alignment	○ SSD ○ Design speed, Curve radii and superelevation ○ Terrain ○ Drainage	1) Minimum radius 2) Relation between design speed, superelevation, and friction factor	○ Drainage becomes important to avoid waterlogging that affect ODD, especially where superelevation is low or zero - Horizontal curves on low-speed streets in urban areas designed without superelevation will require modification as water logging should be avoided for AV related road infrastructure ○ Correlation between horizontal curvature and the automated speed ○ Communication and Connectivity can further improve safety -Sight Distance on Horizontal Curves
Vertical Alignment	○ SSD ○ Length of vertical curve ○ Grade's difference effects grade is more pronounced on the operating characteristics of trucks than on passenger cars -may introduce undesirable speed differentials between the vehicle types	Crest Vertical Curve Stopping, or passing sight distance controls	○ Influenced by the height of sensors and angle of inclination of the headlight beam -AV presents opportunity for optimizing vertical alignment for designing AV only infrastructure -Existing design can be assumed for shared infrastructure ○ Bad weather impact SSD for AV
		Sag Vertical Curve Headlight/SSD distance, comfort, drainage, and appearance control	
Drainage Facility Placement	1) Drainage- surface run-off 2) Space availability	Refer Chapter 2, section 7 (page 2-53 to 2-61) for design information on Drainage Facility Placement	○ High priority for drainage for AV related road infrastructure - Surface water accumulation may cause the AV systems to become 'paralyzed' ○ Improving the design and maintenance of drainage infrastructure (e.g., culvert. channels and gullies) should be given higher priority

Table 17 Basic design criteria and design considerations for AV- part 2

Design elements	Influencing factors	Existing practice	Design consideration under AV
Pavement Cross Slope	Drainage	up to 2 percent	Remains same, modification required wherever drainage is not enough
Median Design	1) Opposing traffic streams 2) Type and location of the highway or street facility	4 ft to 76 ft	Remains same, Head-on collisions should be avoided under any circumstances (system failure)
Lane Widths	1) Operational characteristics of design vehicle 2) Road's functional classification 3) Safety 4) Bicycle accommodations 5) Psychological attributes of human drivers	1) 12 ft minimum: high-speed all freeways and most rural arterials 2) 11 ft or 12 ft: low-speed urban streets	Width can remain same for shared lanes and narrower lane can be proposed for specific lane cases: 1) Dedicated lanes 2) Roads with low traffic volume 3) Urban street- areas defined by ODD etc., Note: **Road dieting with capacity**: capacity increase (expected benefits of AVs) on freeways above an acceptable rate presents opportunity for road dieting/ safe retrofitting existing design to incorporate dedicated infrastructure with communication module to provide connectivity (*197*, *198*) (*195*)
Shoulder widths	Refer to NCHRP Report 254, Shoulder Geometrics and Use Guidelines (*199*)	2 ft on minor rural roads with no surfacing 12 ft on major roads where the entire shoulder may be stabilized or paved 5 ft minimum for bridges being replaced or rehabilitated	AV technology specifies the vehicle to park on the nearest shoulder (either inside or outside shoulder) in case of an emergency

Sidewalks and Pedestrian Elements	Sidewalk Location	buffer space of 4 ft to 6 ft	Higher market penetration of AV will lead to significant changes in the street design and curb side activities, and important cross-sectional elements are predicted to change
	Sidewalk Width	Minimum: 4 ft Sidewalk immediately adjacent to the curb: 6 ft Areas with concentrated pedestrian traffic: 8 ft	Remains same Can be increased at location where lane reduction or lane width reduction is possible
	Walking Speeds	3.0 to 4.0 ft/s	Remains same
	Street Crossings		Remains same -Can be reduced for AV only streets, low traffic shared streets
	Curb Ramps and Landings		Remains same
	Cross Slope	Maximum 2 %	Important to avoid water logging
	Street Furniture		Remains same (additional infrastructure/ instruments may be developed to support AV operations)
Curb and Curb with Gutters	Vertical curbs	6 inches or higher	Remains same
	Sloping curbs	6 inches or less 4 inches or less (preferable)	Remains same
Roadside Design	Safety	Refer chapter 2, section 7, page 2-48	May be impacted by incidents due to disengagements
Slopes and Ditches	Safety and ease of recover of out-of-control vehicles	relatively flat areas adjacent to the travel-way	Important to consider the safety maneuvers of level 3-4 AVs when automation fails, and drivers does not respond for taking control of driving
Lateral Offset to Obstructions	SSD Lane capacity Parking and other curbside activities	1 ft to 1.5 ft minimum	Important to keep track future roadside infrastructural needs to support and enhance the AV ODDs, esp. on urban streets
Clear Zone	Safety	Table 2-12: Clear Zones	May need to be modified based on recommendations considered for shoulders - Should increase if increase in width of shoulders is proposed -Important to consider safe harbor areas for AV in case of automation system failure

Section 3: New Location and Reconstruction (4R) Design Criteria

Urban Streets

This section primarily focuses on road design elements related to the urban environment. Insights from literature indicate that under mixed traffic conditions with no dedicated lanes, the majority of the roadway design elements will still be regulated by requirements/limitations of human drivers. Nevertheless, additional provisions should be incorporated for the AVs to operate efficiently, for instance, sensors in the medians, colored lane markings, etc. (See Table 19 for more details). Dedicated lanes can help minimize conflict points and achieve safe traffic operations. However, it must be noted that although vehicle sensors are programmed to read and detect the road infrastructure, signage, and road markings, it may be challenging for the AV to recognize them correctly in an ambiguous or adverse environment (for example bad weather, poor visibility, etc.). For this purpose, it may be beneficial to install V2I infrastructure that can communicate the traffic control measures (such as speed limits) along with road signages (such as stop signs) digitally with the vehicles. The below sections present an overview of the proposed changes in each design element under dedicated and non-dedicated lane scenarios. The proposed changes are summarized more succinctly in Table 19.

Design Speed

The design speed of vehicles is not expected to change unless complete automation is achieved. This is because even though AV technology provides enough scope to increase design speed increase in vehicle crashes may be expected due to higher speed differentials or reduced pavement tire interactions.

Shoulders

Shoulders are useful for the vehicles to make a halt in case of emergencies. The existing width of shoulders (10 feet) is sufficient for the vehicle to make an emergency stop. However, as the vehicle technology advances towards vehicle automation it is expected that there would be an increase in the number of vehicles making an emergency halt on the shoulders. Hence it is recommended to have increased area of shoulders to accommodate this increase in demand.

Medians

The primary purpose of the median is to separate opposing flows and provide storage space for turning lanes. Under mixed traffic conditions, the median layout most likely will remain unchanged except that sufficient incorporations in the AVs controls must be made for the AVs to recognize medians. However, if the inside lanes are dedicated to AVs, an unwarranted increase in conflicts can arise between through moving AVs and left turning vehicles at intersections. Henceforth AVs must be able to maneuver over such conflicts else it can lead to traffic instability.

Median Openings

No major modifications may be required for the median openings if sufficient provisions are made in the AVs to recognize the surrounding infrastructure.

Intersections

Geometric design of intersections under mixed traffic conditions will remain unchanged. However, when the road space is occupied by connected AVs the requirement of sight triangles maybe eliminated, and the intersections can be skewed as opposed to preferred 75° to 90°. However, having skewed intersection is possible only when the vehicles are completely autonomous, design guidelines are not expected to vary under mixed traffic conditions. It is also important to notice that for safer operation of AVs signalized intersections are preferred compared to unsignalized intersections since a variety of movements in an unsignalized intersection require human decision making which may be difficult for an AV to manage especially at early stage of level 3 or 4 for AVs.

Speed Change Lanes

These lanes are primarily provided in urban roads for the vehicles to decelerate before approaching an intersection. AVs, which are expected to have higher deceleration rates, can come to halt faster than humans, hence they might require short deceleration lengths (subjected to passenger comfort) when compared to HDVs. However, storage length is expected to remain same irrespective of vehicle type. It is important to mention that higher deceleration rate could have a discomfort effect on human passengers and yet more consideration shall be considered to what extent these rates can be increased.

Bus Lanes

Integration of AVs into the bus lanes is highly recommended in urban conditions especially if there is limited ROW. This can form an ideal solution, especially in the initial stages when the market penetration of AVs is low. For the locations without bus lanes, inside lanes can be dedicated for HOVs and AVs allowing physical segregation and limited access points.

Geometric Design Criteria for Urban Streets

Table 18 presents a summary of potential changes that should be incorporated to various road elements with respect to the design criteria given in RDM. Rationale behind these changes is presented in Table 19.

Table 18 Geometric design criteria for urban streets after AVs

Item	Functional Class	Desirable	Minimum	Mixed Traffic	Dedicated Lanes
Design Speed (mph)	All	Up to 60	30	Remains same	Remains same
Horizontal radius	All	See Table 2-3 and Table 2-4 and Table 2-5 in RDM		Remains same	Remains same
Maximum Grade (%)	All	See Table 2-9 in RDM		Remains same	Remains same
Stopping Sight Distance (ft)	All	See Table 2-1 and Figure 2-3 in RDM		Remains same	Can decrease only if the infrastructure is solely dedicated to AVs. However, if the infrastructure is shared by both HDVs and AVs then no modifications are expected
Width of travel lanes (ft)	Arterial	12	11	Remains same	Can decrease
	Collector	12	11	Remains same	-
	Local	12	11	Remains same	-
Curb Parking Lane Width(ft)	Arterial	12	10	Should increase	Should increase
	Collector	10	8	Should increase	Should increase
	Local	9	8	Should increase	Should increase
Shoulder Width, Uncurbed urban streets (ft)	Arterial	10	4	Should increase	Should increase
	Collector	8	3	Should increase	Should increase

	Local	8	2	Should increase	Should increase
Width of Speed Change Lanes (ft)	Arterial and collector	11 to 12	10	Remains same	Can decrease
	Local	10 to 12	9	Remains same	Can decrease
Offset to Face of Curb (ft)	All	2	1	Remains same	Remains same
Median Width	All	See Medians section in Urban Streets of RDM		See Table 7	
Border Width (ft)	Arterial and collector	20	15	Remains same	
	Local	10		Remains same	
Clear Sidewalk Width (ft)	All	6 to 8	5	Remains same	
On-Street Bicycle Lane Width (ft)	All	See Chapter 6, Bicycle facilities in RDM		Remains same	
Superelevation	All	See Chapter 2 superelevation rate, Superelevation Transition Length, Superelevation Transition Placement, Superelevation Transition Type in RDM		Remains same	
Clear Zone Width (ft)	All	See Table 2-12 in RDM		Should increase	Should increase
Vertical Clearance for New Structures (ft)	All	See Table 2-11 in RDM		Remains same	
Turning Radii	-	See Chapter 7, Minimum Designs for Truck and Bus Turns		Remains same	

Table 19 Proposed modifications for urban streets under mixed traffic and dedicated lane

Design Elements		Existing Design conditions	Modifications proposed	
			Mixed Traffic	**Dedicated Lane on the inner side of road**
Median	Raised Median	Desired where ADT 1) > 20000 veh/day 2) when mid-block left turns and turn around volumes are high	1) The existing design values are not expected to change by much especially if the medians are used as pedestrian refuge islands. 2) Width of medians are also expected to be the same.	1) The existing design values are not expected to change 2) Width of medians are also expected to be the same 3) Can have increased conflicts as discussed subsequently.
	Flushed Median	These allow for traversing along them and do not permit left turns; however, the left turns are not regulated	Can be embedded with sensors to enhance the detectability for AVs.	Having a dedicated lane for AV along the median side of road leads to conflicts with HDVs at left turn points, that warrants for efficient weaving from AVs. Inefficient weavings can lead to deterioration of traffic performance.
	Two Way Left Turn Lanes (TWLTL)	Width of TWLTL is given in Table 3-2 of RDM	Existing design widths are not expected to change, however, to support AVs' movement the medians may be equipped with sensors to communicate with vehicles.	Provision of dedicated lanes along with the TWLTL may not be viable since such design can lead to conflicts between conventional vehicle left turns and AVs.
Median Openings		Several types of openings are provided in figure 3-1 of RDM	Existing width of openings should still be sufficient provided the machine vision is able to detect it. However, embedded sensors or suitable retroreflective markings should be used to assist the operation of AVs.	The width of median openings under dedicated lane can become ambiguous. Therefore, further research is essential to make suitable conclusions.

Intersections		The turning radius of trucks, cars and sight distance play a decisive role in intersection sight distance	Sight triangles of AVs can be greatly improved for AVs (especially that are higher than level 3). However, longitudinal markings along the intersection can complement the digital mapping of AVs.	Design specifications as provided in mixed traffic conditions hold. Further, having a dedicated lane can reduce the intersection capacity since sufficient consideration must be provided for maneuvers as discussed in medians section.
Speed Change Lanes		Length of deceleration lanes is determined by storage length and deceleration length (see table 3-3 through table 3-4 in RDM), mostly governed by storage length	The overall length is not going to vary significantly under mixed traffic conditions	If the ROW allows for dedicated lanes, then the length of deceleration lanes can be shorter than the existing ones because of higher deceleration/acceleration rates of AVs and greater sight distance. However, the magnitude of decrease is a constraint of passengers comfort since increased acceleration/deceleration rates lead to discomfort of travel.
Bus Lanes	Curb Bus Lanes	They are usually implemented during peak hours with the removal of curb parking	These should have conflicts with right turning vehicles, therefore it is essential for AVs to be able to yield for such vehicles. Having dotted markings is essential.	Provision of dedicated lane for AVs along with bus lanes can be impractical especially due to extremely restricted availability of ROW
	Median Bus Lanes	These are generally implemented throughout the day but can have conflicts with left turn movements	1) Physical segregation from conventional drivers may be required on either side. 2) May have conflicts at the entry and exit points	Not an economically feasible option

Suburban Roadways

Most of the design elements in suburban roadways are akin to the elements of urban streets with the only difference being the design speed (For more details refer to Table 3-5 in RDM). Therefore, modifications proposed in the earlier section are still valid and applicable to the present section (See Table 19). However, due to higher operating speeds on suburban roadways, a few road elements are designed based on the design speed of rural roads. The section below describes such elements that have a different design from urban streets.

Access Control

Since suburban roadways extend beyond the urban fringe typically it has higher operating speeds. Usually, access points are provided at commercial establishments for the entry/exit of vehicles. For the AVs to recognize them, additional infrastructure or signages may have to be installed.

Speed Change Lanes

For the length of speed change lanes in suburban roads with moderate traffic it should be possible to maintain shorter deceleration lengths for AVs if dedicated lanes are provided. However, it should ultimately depend on the operating speed and comfort of the passengers.

Clear Zones

Existing provisions of clear zone widths are provided in Table 2-12 of RDM, however as discussed in earlier sections the width of clear zones should increase when AVs reach high market share. This is essential to handle the disengagement of vehicles.

Intersections

As explained in the urban street's sections, AVs can intersect at any preferred angle (provided unobstructed vision exists) if minimum turning radius is being provided. Moreover, it was identified that AVs can perform more efficiently under signalized intersections rather than unsignalized intersections.

Two Lane Rural Highways

This section deals in identifying the changes that may take place after the introduction of AVs. Provision of dedicated lane along two lane rural highway may be impractical with the amount of ROW available. Therefore, under mixed traffic conditions, since humans are going to be the decisive factor, the design criteria are still going to remain same. However, it is possible to have a limited ODD completely operated by AVs. Hence, Table 20 summarizes basic design criteria for rural two-lane highways considering AVs. Moreover, Table 21 proposes changes that should be incorporated if the road segment is completely occupied by the AVs.

Table 20 Geometric design criteria for two lane rural highway after AVs

Item	Design Value	Modifications under AVs
Design Speed (mph)	Table 3-7 in RDM	Remains same
Minimum Horizontal radius	Table 2-4 and Table 2-5 in RDM	Remains same
Maximum Grade (%)	Table 2-9 in RDM	Remains same
Stopping Sight Distance	Table 2-1 in RDM	Remains same
Width of Travel lanes (ft)	Table 3-8 in RDM	Should decrease
Shoulder Width (ft)	Table 3-8 in RDM	Should increase
Vertical Clearance for New Structures (ft)	Table 2-11 in RDM	Remains same
Clear Zone width (ft)	Table 2-12 in RDM	Should increase
Passing sight distance	Table 3-9 in RDM	Remains same
Superelevation	Chapter 2, Superelevation Rate, Superelevation Transition Length, Superelevation Transition Placement, Superelevation Transition Type	Remains same
Turning Radii	Chapter 7, Minimum Designs for Truck and Bus Turns in RDM	Remains same

Table 21 Proposed modifications for two lane rural highways under AVs

Design element		Existing techniques	Modifications under AVs
Access Control		Frontage roads are not allowed along two-lane rural highways, RDM says it can confuse an unfamiliar driver.	Frontage roads or parallel service roads can be provided in the case of CAVs since they communicate with the surrounding infrastructure.
Passing Sight Distance		Recommended passing sight distances are based on the assumptions provided in section “Passing sight distances” of RDM	All the existing conditions are subjected to change when only Level 3 and above vehicles exist on road, under such circumstances existing recommendations need to be revised. However, under mixed traffic conditions with the presence of level 2 or below SAE levels modifications are not expected.
Speed Change Lanes	Climbing Lanes	Provided when one of the following exists: 1) 10 mph or greater speed reduction is expected for a typical heavy truck 2) LOS E or F exists on the upgrade 3) A reduction of two or more levels of service is experienced when moving from the approach segment to the upgrade	No modifications proposed
	Left Turn Deceleration Lanes	Left turn lanes are economically unjustified and should be delineated with striping’s and markers	No modifications are proposed
	Right Turn Deceleration/ Acceleration Lanes	For two lane highways provisions of right turn acceleration/deceleration lanes are considered inappropriate since these can confuse the drivers.	With vehicle automation, the confusion can be avoided, and acceleration/deceleration lanes can be provided. However as long as HDVs exist no modifications can be anticipated.
Intersections		Depends on 1) Intersection sight distance 2) Preferred angle of intersection is 75 to 90 degrees	Level 3 and above AVs have improved sight triangles, therefore skewed intersections can be incorporated under connected autonomous environment provided it can have sufficient turning radius. However as long as HDVs exist no modifications can be anticipated.

Multi-Lane Rural Highway

This section discusses the modifications that should be required for multilane rural highways. Predominantly, this section focuses on six-lane divided, four-lane divided, and four-lane undivided highways. Similar to earlier sections it is identified that the design criteria for most of the elements should remain the same under mixed traffic in the absence of dedicated lanes. However few aspects such as shoulder width are bound to change when AVs are introduced. The following sections describe the changes that should be incorporated in the design elements. Table 22 presents the summary of anticipated changes in geometric design criteria and Table 23 explains the modifications needed for multi lane rural highways.

Access Control

Provision of access for multilane highways is provided in accordance with TxDOT access management manual. It is understood that AVs may not change the location of access points substantially. However, provisions are to be made for AVs to understand the entry/exit points.

Medians

In Multilane rural highways, it is desirable to provide wide medians since they can provide storage space, reduce headlight glare, and improve traffic safety. However, when there is limited ROW or if the locality is likely to become suburban or urban, narrow surface medians are preferred. Whereas in the case of AVs, it is important to notice that aspects such as reduced headlight glare, improved safety becomes redundant providing an opportunity to reduce the median size. However, even under the existing AV technology it is unfeasible to have narrow medians due to the possibility of head on collisions.

Median Openings

Median openings are spaced such that through traffic is not perturbed. Moreover, the width of openings is based on the turning radius of trucks. Hence the design criteria for median openings are not believed to vary significantly under AVs.

Turn Lanes

These lanes act as a transition for the vehicles entering/exiting onto the highways. Since AVs are expected to have higher deceleration rates/acceleration rates the deceleration lengths and acceleration lengths provided in Table 3-12 and figure 3-14 respectively in RDM can be shorter provided sufficient passenger comfort is maintained. Taper lengths, storage lengths depend on the design speed and turning volume respectively, therefore it is not expected to vary much in the case of AVs. Further lane adjustment factors given in Table 3-14 of RDM may have to be revised under full penetration of AVs.

Travel Lanes and Shoulders

Typically, the width of travel lanes along a multilane rural highway is 12 ft. This width can be reduced for dedicated AV lanes based on the dimensions of the design vehicle whereas the lane width should remain same if dedicated lanes are not provided. Moreover, the width of shoulders may increase under both mixed and dedicated traffic conditions since AVs, which are higher than level 3, are programmed to halt on shoulders under emergency situations.

Intersections

The design of intersections is based on providing sufficient sight distance to drivers and adequate turning radius to the trucks and bus as defined in chapter 7 of RDM. For this reason, right angle intersections are preferred over skewed intersections. Since CAVs can communicate with other vehicles and AVs can have larger sight triangles it is possible to have skewed intersections in fully autonomous conditions provided minimum turning radius can be guaranteed. However, such modifications are not expected to be implemented unless there are no HDVs and a high penetration of connected AVs. Moreover, CAVs may require having V2I infrastructure embedded in the splitter islands near non-signalized intersections.

Transition to Four Lane Divided Highways

The transition of a highway from two to four lanes is usually designed based on the driver's visibility and perceivability. Such operations can be baffling for AVs especially if the existing alignments are converted as shown in figure 3-16 of the RDM. In such cases, simple provision of signages may not be sufficient and may require additional infrastructure or colored markings which can communicate with the AVs. Current practice of AV industry is to digitally map the road and when there is such lane drops or increase in lanes, the transition zone becomes extremely crucial for AVs. Therefore, it necessitates to have an additional improvement such as dotted markings (similar to gore areas), colored markings, additional signages etc. Such changes help AV perceive the change in environment. These changes should be applicable even when there is a dedicated lane.

Table 22 Geometric design criteria for multi lane rural highway after AVs

Design elements	Functional class	Existing design values	Proposed modifications	
			Without dedicated lane	Dedicated AV lane
Design Speed (mph)	All	As per Table 3-11 of RDM	No modifications proposed	No modifications proposed
Median Width (ft)	All	As per Table 3-11 of RDM	No modifications proposed	No modifications proposed
Lane Width (ft)	All	As per Table 3-11 of RDM	No modifications proposed	Can decrease but depends on the dimension of the design vehicle
Shoulder Width (ft)	All	As per Table 3-11 of RDM	Should increase since level 3 and above AVs are programmed to halt on shoulders during emergencies	Should increase since level 3 and above AVs are programmed to halt on shoulders during emergency situations
Min. Structure Widths for bridges to Remain in Place (ft)	All	As per Table 3-11 of RDM	No modifications proposed	No modifications proposed
Vertical Clearance, New Structures (ft)	All	As per Table 2-11 of RDM	No modifications proposed	No modifications proposed

Minimum Horizontal Radius	All	Table 2-4 and Table 2-5 in RDM	No modifications proposed	No modifications proposed
Stopping Sight Distance	All	Table 2-1 in RDM	No modifications proposed	Higher sight distance of AVs cannot be taken advantage of, even with dedicated lanes as long as AVs share the road infrastructure along with HDVs. Therefore, modifications are not expected.
Maximum Grade (%)	All	Table 2-9 in RDM	Remains same	Remains same
Clear Zone	All	Table 2-12 in RDM	Should increase	Should increase
Superelevation	All	Chapter 2, Superelevation Rate, Superelevation Transition Length, Superelevation Transition Placement, Superelevation Transition Type	Remains same	Remains same
Turning Radii	All	Chapter 7, Minimum Designs for Truck and Bus Turns	Remains same	Remains same

Table 23 Proposed modifications for multi lane rural highways under AVs

Design elements		Existing design criteria	Proposed modifications	
			Without dedicated lane	Dedicated AV lane
Access Control		In accordance with TxDOT Access Management Manual	No modifications proposed	No modification proposed
Deceleration Lanes	Left Turn Lane	Deceleration lane width depends on the median width; deceleration lane length = sum of deceleration lane and taper lanes	No modifications proposed	AVs can have greater deceleration rates hence shorter lanes can be maintained; however, the lengths ultimately depend on the passenger's comfort and as long as AVs share the road infrastructure with HDVs no modifications are expected.
	Right Turn Deceleration Lane	Deceleration lane width depends on the right lane width and width of shoulders; deceleration lane length = sum of deceleration lane and taper lanes	No modifications proposed	AVs can have greater deceleration rates hence shorter lanes can be maintained; however, the lengths ultimately depend on the passenger's comfort and as long as AVs share the road infrastructure with HDVs no modifications are expected.
Acceleration Lanes		Given in Fig 3-14 in RDM	No modifications proposed	AVs can have greater acceleration rates, but the lengths ultimately depend on the passenger's comfort and as long as AVs share the road infrastructure with HDVs no modifications are expected.
Intersections		It depends on the intersection sight distance and turning angles. Details of it are available in Chapter 2. Preferable angle of intersection is 90 degrees and should not intersect less than 75 degrees.	No modifications proposed	Under complete autonomy, AVs can intersect at any angle therefore may have skewed intersections but ultimately depends on the turning radius as given in chapter 7 of RDM. AVs prefer signalized intersections over unsignalized intersections. Further as long as AVs share the road infrastructure

			with HDVs no modifications are expected.
Transition to Four Lane Divided Highways	Typical transitions are given in Fig 3-16 in RDM	Additional infrastructure/sensors/colored markings may be required.	Additional infrastructure/sensors/colored markings may be required.

Freeways

This section details the modifications that should be required for freeways. It is identified from the existing literature that freeways usually have minimal number of conflict points making it easy to deploy the AVs in the initial stages when the technology is still immature. Similar to other road types, minimal modifications are expected when there is still a human element involved however when dedicated lanes are provided numerous changes are expected. Further details are summarized in Table 24.

Table 24 Proposed modifications for freeways under AVs

	Classification	**Design conditions**	**Proposed modifications**		**Remarks**
			Without dedicated lane	**Dedicated lane**	
Design Element	Stopping Sight Distance	Table 2-1	Remains same	Remains same	As observed earlier the improved sight distance should not benefit presuming that AVs still share the road infrastructure with HDVs.
	Clear Zone	As per Table 2-12 in RDM	Need to increase	Need to increase	The width of clear zones may need to be increased since AVs are currently being programmed to come to a halt on the shoulders.
	Maximum Grade (%)	As per Table 2-9 in RDM	No modifications proposed	No modifications proposed	If complete automation is attained provision of steeper grades aligning with a natural profile can be provided. However, ultimately the design condition depends on the design vehicle's ability to ascend.

	Minimum Horizontal Radius	As per Table 2-3 and Table 2-4 in RDM	No modifications proposed	No modifications proposed	No modifications are proposed since vehicle dimensions may not be altered under vehicle automation
	Superelevation	Chapter 2, Superelevation Rate, Superelevation Transition Length, Superelevation Transition Placement	No modifications proposed	No modifications proposed	No modifications are proposed since the horizontal radius and friction coefficient remains same
	Vertical Curvature	As per Figures 2-6 and 2-7 in RDM	No modifications proposed	No modifications proposed	Improved sight distances in the case of AVs provide scope for reduced cut and fill of natural profile. Nonetheless, the vertical curve design depends on the design vehicle's ability to mount the curve without considerably affecting traffic safety and operations.
	Pavement Cross Slope	As given in chapter 2 Pavement cross slope of RDM	Remains same	Remains same	Stagnation of water must be avoided since Level 3 vehicles may fall out of DDT and alert drivers
	Turning Radii	Minimum Design for Truck and Bus Turns	Remains same	Remains same	Vehicle automation does not alter the vehicle lengths, therefore remains unaltered
Access Control	Spacing between exit ramps and driveway, side streets or cross streets	As per Table 3-16 of RDM	No modifications proposed	No modifications proposed	Vehicle automation improves the co-operation level among the vehicles, hence efficient traffic operations can be obtained within short distance. Therefore, the separation distance between ramps entrance/exit and driveways or side streets can be reduced. However, since having dedicated lanes along freeway does not assure the elimination of AV-HDV interaction after exiting freeways. Therefore, the existing criteria of maintaining

					sufficient distances between ramps and driveways/streets still holds
Main Lanes	Design Speed	Table 3-17 in RDM	No modifications proposed	No modifications proposed	Increase in design speed can pose challenge for safety of vehicles. Hence, they are not expected to increase until significantly high level of automation is achieved.
	Lane Widths	12 ft	Remains same	Can be reduced	The width of lanes can be decreased under automated traffic
	Shoulder Widths	As specified in Table 3-18 of RDM	May increase	May increase	Current AV technology specifies the vehicle to park on the nearest shoulder (either inside or outside shoulder) in case of an emergency. Hence this mandate for a continuous extended shoulder
	Medians	24ft to 76ft based on the number of lanes	No modifications proposed	No modifications proposed	Median widths on freeways are generally built anticipating future traffic, hence vehicle automation does not warranty for any change in the width of structure.
Frontage Roads	Design Speed	Chapter 3 Frontage Roads in RDM	No modifications proposed	No modifications proposed	Frontage roads are characterized by large number of weaving operations. Hence higher design speeds may result in formation of extended shockwaves.
	Design Criteria	As per Table 3-19 of RDM	No modifications proposed	Existing lane width is to be maintained	Existing width of lanes may have to be maintained particularly when the frontage roads meet on-ramps or off-ramps to support smooth merging and diverging operations
Inter-changes	Spread Diamond	Spread diamonds when used enhances intersection sight distance. However, it requires an additional ROW.	No modifications proposed	Requirement for additional ROW can be eliminated	The requirement for additional ROW can be averted when all the vehicles are at higher than Level 3

Ramps and Direct Connect-ions	Design Speed	As per Table 3-20 of RDM	No modifications proposed	No modifications proposed	No modifications are proposed because it is anticipated that it can escalate the speed differentials which can compromise the traffic safety
	Ramp Geometrics	Entrance Ramp Exit Ramp	No modifications proposed	No modifications proposed	AVs can have greater acceleration/deceleration rates. Hence, shorter ramps can be provided, provided there are no HDVs along the segment. However, the lengths ultimately depend on the passengers' comfort.
	Gores	For instance, similar to given in figure 3-34	Must have chevron markings	Must have chevron markings	Gore area must have uniformity in the form of having chevron markings for AVs to detect. (Further research on the impact of chevron marking on Safety is recommended)
	Cross Section and Cross Slopes	As provided in Table 2-3 or Table 2-4 of RDM	No modifications proposed	No modifications proposed	No modifications proposed (However, it is highly recommended to have slopes that prevent stagnation of water. This is especially important because level 3 and above vehicles can regard them as objects and try to perform DDT fallback)
	Sight Distance	Current conditions direct to have an additional 25 percent stopping sight distance at the nose of an exit ramp of freeway	No modifications proposed	No modifications are proposed	Once the V2I communication is established, Level 3 and above vehicles can detect the exit locations from distant locations thereby resulting in lesser sight distance.
	Grades and Profiles	Design speed (mph) / Max Grade 25-30 / 7% 35-40 / 6% >40 / 5%	No modifications proposed	No modifications proposed	Steeper grades can be achieved when full automation is achieved. However, grades are controlled by the ability of the design vehicle to climb the slopes

Access Control under Complete Automation and Connected Automation

Frontage Road Access

The section "Frontage Road Access" in chapter 3 of RDM describes on several design considerations that needs to be examined while providing spacing between the entrance/exit ramps and driveways, streets along frontage roads. One such considered design criteria is "traffic operation" which is contemplated to degrade when insufficient spacings are provided. However, when there is complete automation, the vehicles have greater sight distances which invites for increased co-operation in change of lanes that allows for more organized merging and diverging. Such increase in co-operation among vehicles provides the scope to decrease the length of "weaving zone" provided rest of the criteria's mentioned in RDM satisfied. Further when connectivity is established substantial decrease in weaving lengths can be expected warranting for remarkable changes.

Freeway Corridor Enhancements

HOV Lanes

During the initial deployment of AVs, allowing AVs to access HOVs can foster the penetration of AVs. Therefore, it is essential to maintain a uniformity of traffic devices or markings that designate HOV lanes.

Peak Hour Lanes

Usually shoulders are considered emergency stop locations for level 3 and above AVs, hence in those regions where shoulders are used as peak hour travel lanes, deployment of AVs must be done after careful reconsideration without compromising on the safety of travel.

Texas Highway Freight Network (THFN)

With the goal of becoming the most efficient state in freight transportation, TxDOT has provided guidance for vertical clearance policy. According to this policy, all the structures on THFN must have a clearance as specified in Table 2-11 of RDM and pedestrian crossovers must be 1 ft higher than the minimum clearance specified for vehicles after including the allowances of overlays. These aspects are not expected to change under vehicle automation; however, provisions may be provided for the AV to recognize the THFN corridor. Moreover, the specifications for traffic signs, overhead sign bridges, signals and other overhead utilities should be in accordance with RDM and TMUTCD.

Section 4: Non-Freeway Rehabilitation Criteria (3R)

The basic purpose of these criteria is to extend the pavement service life of the existing roadway infrastructure to promote safety. Here, the scope of 3R projects varies from minor safety to more complex redesign and management processes. According to the RDM, the pavement rehabilitation works includes the following jobs:

1. Resurfacing to provide improved structural capacity and/or serviceability,
2. Removing and replacing deteriorated materials,
3. Replacing or restoring malfunctioning joints,
4. Reworking or strengthening of bases and subbases,
5. Recycling existing materials, and
6. Adding underdrains.

This chapter has provided four tables for rural multilane highways, rural two-lane highways, urban streets, rural frontage road, and urban frontage road specification during this rehabilitation process. However, those values are only guiding values but not mandatory values. The designer may select higher values to provide consistency with adjoining roadway sections. The specifications for the current conditions and the impact of the AV are being discussed below.

Alignment

According to the RDM, the alignment of the existing roadway conditions may remain the same during rehabilitation process if there are no major changes in the existing design criteria. The crash history may be considered for flattening a curve to improve safety. The longitudinal gradient must be as low as possible to increase the sight distance of CAVs which will help the navigation of the autonomous vehicles. The rehabilitation part can also be performed as part of the development of roadway infrastructure to accommodate autonomous vehicles.

Design Speed

According to the RDM, for rehabilitation purposes, the suggested minimum design speed for rural multilane highways is 50 mph; high volume rural two-lane highways and high-volume rural frontage roads is 40 mph; low volume rural two-lane highways, low volume rural frontage roads, urban streets, and urban frontage roads is 30 mph. If the design speed is lower than the minimum standards, reconstruction of the alignment must be considered for both horizontal and vertical gradients. With the vehicle automation the existing design speeds are not expected to vary much especially due to higher vehicle crashes. However, if the safety concerns are addressed an opportunity to increase design speed is attained.

Side and Backslopes

Existing design may not be revised, due to that consideration must be given to roadside safety in the design criteria that are no different between standard vehicles and AVs.

Lane Width

RDM specifies lane widths to be 12 ft for the roadway unless the road is occupied with large trucks. Since AVs can commute in platoons, they should require less lane width when compared to HDVs. If the highway is a high-volume route extensively utilized by large AV trucks, during the construction or rehabilitation process, the lane width can be reduced based on proper study outcomes.

Safety Design

Every section of roadway has safety design criteria for the evaluation of the safety protocol of the roadway. According to the RDM, the safety design inspection is done by collecting data, conducting site inspections, and verifying existing geometry. The basic safety improvement includes the construction of guardrails & headwalls which will remain the same with the inclusion of AVs on highways.

Guardrails

Guardrails should be designed as per the measure mentioned in Section 4.3 of TxDOT RDM. Such measure is not expected to change when the AVs are introduced however V2I transmitter may have to be embedded into the guard rails for the safer operation of AVs.

Headwalls

The headwalls on small (36 inches or less) cross drainage pipe culverts that are inside the clear zones should be removed and sloping (1V:3H or flatter) culvert ends that blend with existing side slopes should be provided, according to RDM. The culvert and headwalls will remain unchanged when AVs are introduced.

Further details are summarized in Table 25 below.

Table 25 Design elements, existing conditions, and proposed modifications for 3R projects

Design Elements	Roadway Types	Classification	Existing Design Conditions	Modifications Proposed	
				Mixed Traffic	Dedicated Lane
Geometric Design	1. Rural Multilane Highways (Nonfreeway)- (Table 4-1) 2. Rural two-lane highways (Table 4-2) 3. Urban streets (Table 4-3) 4. Rural frontage roads (Table 4-4), and 5. Urban frontage roads (Table 4-5)	Design speed	Table 4-1, 4-2,4-3,4-4, & 4-5	No modifications are proposed	No modifications are proposed
		Lane Width	Table 4-1, 4-2,4-3,4-4, & 4-5	No modifications are proposed as HDVs have greater wheel wander.	Minimum lane width can be provided since AVs can travel in a shorter space with less wandering due to various ADAS.
		Outside Shoulder	Table 4-1, 4-2,4-3,4-4, & 4-5	May require wide shoulders. Since existing shoulders should not be sufficient if AVs make a halt due to any failure.	May require wide shoulders. Since existing shoulders should not be enough to achieve minimal risk condition when an AV encounters ADS failure or exit its ODD.
		Inside Shoulder	Table 4-1, 4-2,4-3,4-4, & 4-5	May require wide shoulders. Since existing shoulders should not be sufficient if AVs make a halt due to any failure.	May require wide shoulders to accommodate emergency halt of AVs
		Turn Lane Width	Table 4-1, 4-2,4-3,4-4, & 4-5	No modification is proposed	No modification is proposed

		Clear zone	Table 4-1, 4-2,4-3,4-4, & 4-5	No modification is proposed	No modification is proposed
		Bridges Width To be Retained.	Table 4-1, 4-2,4-3,4-4, & 4-5	No modifications proposed since vehicle dimensions may not be altered under vehicle automation.	No modifications proposed since vehicle dimensions may not be altered under vehicle automation.
Safety Designs		Guardrails	Guardrails should be upgraded to current hardware standards.	No modification is proposed	No modification is proposed
		Headwalls	Small headwalls must maintain (1V:3H or flatter) Slop	No modification is proposed	No modification is proposed

Section 5: Non-Freeway Resurfacing and Restoration (2R)

The restoration process consists of tasks that are needed to restore pavement quality, riding quality, and other necessary components to their existing conditions. The addition of through travel lanes is not allowed under the restoration process. However, the addition of turning lanes, shoulders, and acceleration/deceleration lanes is part of this process. The CAV introduction will highly impact the process as the accommodation of CAV dedicated roadways will need changes in the pavement design of roadways.

Section 6: Special Facilities

The first section of this chapter discusses the off-system bridge replacement and rehabilitation projects. The qualifying conditions of this project are facilities not likely to be added to the designated state highway system where the current ADT being 400 or less. The ADT growth in future must be considered while determining the need to modify the design section in the future.

Design Values

The design values should be considered based on the prevalent design feature and existing off-system of the roadway. If the roadway shows a significant increase in ADT in the future, the requirement of the highway should be implemented correctly and precisely. The design criteria are:

1. Minimum Design Speed
2. Vertical Curvature
3. Horizontal Curvature
4. Minimum Superelevation
5. Minimum Superelevation
6. Maximum Grades
7. Minimum Structure Width
8. Bridge End Guard Fence
9. Approach Roadway
10. Traffic Control

These design criteria are discussed in Table 26 in terms of both mixed traffic conditions and dedicated AV lanes. The gradient and slope should be kept as low as possible for the smooth operation of AVs. Guard rails for safe operation of vehicles will remain the same as they have no impact on the operation of AVs. According to the RDM, the traffic control devices when provided should comply with the TMUTCD which is likely to be unaffected and can be developed for the operation of AVs on specific segments.

Texas Parks and Wildlife Department (TPWD) and Park and Wildlife Projects

This section discusses on special design modification for the designated area of TPWD facilities for the betterment of wildlife and other facilities. The design criteria given by the current publication of TPWD Design Standards for Roads and Parking must be followed for the design of these segment of the roadway which has TPWD facilities. The major changes in design are lowering the speed and providing more guidance signs to help the driver for better navigation. This section will remain unchanged by the inclusion of AVs.

Bicycle Facilities

This section deals with the design guidelines for bikeways to accommodate people of all ages and abilities. Bikers and bicyclists are used interchangeably in this section.

Planning and Context

Providing a bicycle facility with minimum dimensions alone may not ensure a safe and comfortable bike ride as bicyclists operate with or adjacent to motor vehicles. All the roadway users should be informed about the presence of bicyclists, especially around major conflict points (intersection, driveway, sidewalks). This will make the AV cautious while navigating these points.

As per section 6.4.2.3 of the RDM, there are three types of bicycle facility users: interested but concerned, somewhat confident, and highly confident. The design is commonly done considering the largest group of potential bikeway users which are the interested but concerned bicyclists. These riders are more likely to take shorter trips and would ride more if they felt safer. Providing a dedicated lane along with separation from the vehicle flow might be the ideal case to improve the efficiency of both the bicyclist and AVs. However, it may not be possible to do so in certain locations due to the low availability of ROW.

Speed, and Volume of Vehicles, and Traffic Mix

Increase in speed and volume of motor vehicles along with the presence of a high proportion of trucks and buses produces discomfort and risks for bicyclists. Moreover, the presence of larger vehicles also impedes the line of sight for vehicles, thereby creating blind spots which may have serious consequences for the bicyclists. In mixed traffic conditions as well as a fully autonomous case, the above-mentioned problem still exists. Hence, providing a dedicated and separated bike lane which in turn minimizes the interaction between bicyclists and motor vehicles is recommended.

Bikeway Design for Urban and Rural Context

The provision for providing either shared lane, bike lane, or separated bike line in an urban context is based on the volume of vehicles per day and higher of the design or posted speed. This will remain the same under mixed driving conditions. However, in the rural context, shoulders or shared lanes are used by the bicyclist for movement. This might be problematic in the case of AVs as they may be programmed to come to a halt at the shoulder in case of disengagement or system failure. Hence, a separate shared-use path is recommended for bikeway travel in rural areas.

Stopping Sight Distance

Stopping sight distance for a bicycle is the distance needed to bring a bicycle to a complete stop. It depends on the perception and reaction time, initial speed, and braking ability of the user, as well as the coefficient of friction between the wheels and the pavement. No changes are recommended regarding this under AV Environment.

Intersection Sight Distance

Intersections of shared-use paths and roadways are a major point of conflict. Hence, the sight distance should be designed using a combination of SSD for motorists and bikers along their respective paths. Special care should be given when high volume of left and right turn movements of vehicles are encountered. Adequate approach clear space should be provided as per Table 6-3 of RDM. Moreover, vertical obstruction near intersections that includes on-street parking should be set back appropriately to allow enough time and space for AVs to detect the bicyclist and act accordingly (slow down or stop) before the conflict point.

Intersection Elements and Bikeway Lighting

Intersection elements and lighting will help AVs to detect bicyclists and navigate through conflict points safely. Markings for bicycle crossing that aids the bikers to pass through a preferred path in an intersection are recommended to be made uniform across the states. Proper signage should be available for stop or yield behavior so that AVs can be programmed to navigate merge or turn across the path of a bicyclist or pedestrian. Moreover, under high flows and mixed and completely autonomous conditions, if possible, dedicated bicycle signals along with phase separation as discussed in section 6.4.3.8.3 in RDM are preferred to minimize conflicts with the left and right turning vehicles.

Poor visibility at night or inadequate lighting conditions can cause severe ramifications for bikers and AVs. Lighting provides a sense of safety and aids bikers to detect surface irregularities. In the case of AVs, proper lighting facilities may help in sensing bikers from a distance and acting appropriately.

Shared Use Paths Adjacent to Roadways (Side Paths)

Under these operating scenarios the bicyclists and other sidewalk users are entirely segregated from the vehicular movements. Therefore, it eventually minimizes the conflicts between vehicles and bicyclists. Henceforth, the existing design recommendations are still recommended for the considered facility type. An important observation to be noted is that desirable street buffer which is equivalent to clear zone values is expected to increase in the future of AVs which could further reduce the conflicts between vehicles and bicyclists. Therefore, existing recommendations for cross slope and grade, horizontal and vertical geometric design still hold for the shared use paths facility types.

Even in the case of shared-use paths, the role of markings and traffic control devices take a significant position in regard to AVs. As given in RDM for the places where the side paths end or when there is a transition to different types especially at intersections, it is important to relay the possibility of bicyclist movements to AVs. An efficient way to achieve it would be to have uniform traffic signs. Further, the bicycle crossings must be clearly marked to let the AVs expect any kind of movement.

Separated Bike Lanes

Separated bike lane is a common sight in most of the urban and suburban regions and there is a wide range of practice adopted for separating bike lanes from vehicular movement. These include, as specified in RDM, raised medians, curbs, flexible posts, raised lanes, etc. Therefore, similar to traffic signs and traffic control devices consistency of practice is crucial in the method of implementation. This is essential in training the AVs even though the LIDAR in AVs can predict the surrounding movements, the efficiency of an algorithm can be higher when the model is sufficiently trained. Therefore, static entities such as traffic signs, distinct pavement markings, or colored bike lanes can communicate such information far easier to AVs and benefit the performance. Figure 6-20 for the Austin, TX and Raleigh NC and Figure 6-21 in RDM provide such a case which has the distinction of pattern from regular patterns therefore such practices can be highly encouraged with modifications after further investigation.

Signing and Marking

The above discussion proves the point to have a distinct pattern to designate the presence of bicyclists in the surroundings. Currently, there is no standardized approach to mark the bikeways or bike lanes, this provides an opportunity for development to improve the efficiency and safety of both vehicles and bikers. Therefore, as an immediate action step to encourage AV adoption and increase the confidence among stakeholders, Infrastructure Owner Operators (IOOs) should focus on standardizing the bike infrastructure.

Other Considerations

Table 6-11 and Table 6-12 in RDM discusses different approaches of providing separated bike lane (SBL) in one way and two-way traffic. The crash risks presented in the respective tables still hold for AVs. Intuitively, one-way SBL, one-way SBL plus counterflow SBL and one-way SBL pair can be preferred techniques to minimize the conflicts provided the separation is well defined. Median two-way SBL can be highly challenging in safety perspective because of increased conflict points. This would require for additional signal phase as mentioned in Table 6-12.

Buffered Bike Lanes

One more common type of dedicated lane was observed in urban and suburban areas. RDM specifies the classes of markings that are used based on the width between longitudinal marking such as chevrons, diagonals, etc. Having a standardized marking can make a difference for AVs in the case of undigitized networks. Although various types are preferred because of the difference in buffer widths, standardization in terms of having a designated color for bike lanes or additional signages indicating bike lanes is immensely encouraging for AVs.

In signing and marking RDM specifies the possibility of having a 6-inch lane towards the travel lane and a 4-inch towards bike lane which is recommended to 6-inch markings on both sides to improve the visibility of AVs.

Bike Lanes

These lanes are typically used in corridors with low speeds (<45 Mph) travels adjacent to vehicular movement without any buffers provided. Such sections are critical for AVs since they conflict with each other at right turns and it is not uncommon for bikers to pass on travel lanes and switch to bike lanes while passing or to avoid debris. Such kinds of movements are always a challenge for AVs to predict and the distance between them can be too low sometimes which leads to minimal reaction time for AVs. AVs can be ideal for such situations with the highly regarded low reaction time, however, the challenge greatly lies in the ability of lidars to detect the bikers in all environments. The aforementioned behavior is rather related to the efficiency of algorithm than infrastructural modifications. Nonetheless, it is advantageous to be informative of such complexities involved.

A solid edge line, 6-inch-wide is used to separate the bike lane from regular traffic, hence care must be taken to maintain the continuity as far as possible since AVs solely rely on markings in the absence of digitally mapped data.

Raised Bike Lanes

Since these lanes are raised from regular travel lanes, they can be easily detected by AVs. Practices that involve identifying a curb would be applicable. Recommendations provided in RDM can be appropriate for AVs: contrast paving materials, six-inch-wide edge lines, etc. Having bike lane regulatory signs would further benefit. However, the challenge can be at intersections where bikers come to the level of travel lanes leading to conflicts. Proper demarcations in the form of markings can help minimize the conflict areas.

Shared Lanes

This is a case where bikers share the travel lane along with vehicles. Since AVs are required to follow or lead the bikers it is challenging for AVs to predict the behavior of bikers. Moreover, the effect of performance in conditions where the LiDARs efficiency is less than desirable such as adverse environment, poor visibility, etc. is something that needs further investigation.

Intersections and Crossings

The intersection is the most significant point of conflict between vehicles and bicyclists. Proper care must be given while designing an intersection. The chief aim of the designer is to minimize or eliminate the conflict point and provide a continuous movement to and through an intersection.

Intersection Approach Treatments

Various intersection approach treatments are listed in the RDM:

- Shoulder or bicycle lane terminated to a shared through lane
- Shoulder or bicycle lane terminated to a shared right turn lane
- Shoulders and bicycle lanes continue with addition of right turn lanes
- Shoulder transition to bicycle lane
- Shoulder transition to bicycle lane at t-intersections with bypass lanes
- Protected intersection or continuation of separated bike lane or sidepath

Except for the last treatment, all are unprotected and the bicyclist either rides along or crosses the lane with motor vehicles trying to take a right turn. All these treatment approaches are significantly important and complex in mixed and fully automated driving conditions. It is recommended to provide uniform lane markings and signage which may aid AVs to navigate this complex interaction with bicyclists.

For protected intersections, a corner island is provided which sets a horizontal offset between the adjacent roadway and bikeway. This will create a stop or yield zone for motorists. Corner island can also be used to slow down the turning vehicles which increases the comfort and safety of bikers. For an automated scenario, a corner island plays an important role as AVs can stop or yield to pedestrians, bikers, and motorists before taking a turn when it is safe. As discussed earlier, the presence of on-street parking near an intersection may block the line of sight of the vehicles and pedestrians which in turn increases the probability of incidents. Therefore, parking restrictions at an intersection can be done to provide space to install corner islands.

Traffic Control Considerations

Several signs that benefit human-driven vehicles listed in RDM are also applicable for mixed and automated scenarios. Some of them are listed below:

- TURNING VEHICLES STOP TO PEDESTRIANS AND BICYCLES
- BICYCLES ON ROADWAY
- BIKES MAY USE FULL LANE

The onboard sensors present on AVs can read these signs and act accordingly. Hence, it will know when to stop or yield to pedestrians, bikers, and other motorists.

Driveways

Similar to intersections, driveways are a major point of conflict between pedestrians, bikers, and vehicles. Under mixed traffic conditions, the design guidelines given for driveways in RDM can be adopted. It can be supplemented by providing uniform signs and markings that can guide the movement of AVs in and out of the driveways.

Mid-Block Shared Use Path Crossings

Mid-block crossing is of two types: controlled (signalized) and uncontrolled (signing and markings only). For AVs navigating through a controlled mid-block crossing is simple. However, the problem arises when an uncontrolled mid-block crossing is encountered. To be more specific, SAE level 3 vehicles may have a problem in navigating an uncontrolled mid-block as shown in Figure 6-55 of the RDM as they would have to scan around for any bicyclist and yield or stop accordingly.

Roundabouts

Standard bike lanes are not permitted within roundabouts. Separated bike lanes crossings where vehicles have to stop and yield for bikers should be used. Various warning signs such as STOP HERE FOR PEDESTRIANS AND BICYCLES should be used to notify AVs of the available roundabout crossing.

Maintenance, Operations, And Work Zone

An alternative route should be provided for bikers to move through and along the work and maintenance zone safely. It is preferred to provide a separate bike lane to maintain a physical separation from traffic. For AVs, navigating a work zone is a complex task. It has to capture and process a lot of dynamic behavior. However, proper marking and signage for temporary lane closure, changes in traffic operations, alternative paths, etc. can help AVs to maneuver around the work zone safely by detecting other vehicles, pedestrians, and bicyclists.

Table 26 Design elements, existing conditions, and proposed modifications for special facilities

Project name	Design elements	Existing design conditions	Modifications proposed for mixed traffic	Modifications proposed for dedicated lane
Off-System Bridge Replacement and Rehabilitation Project	Minimum Design Speed	Meet or improve conditions that are typical on the remainder of the roadway.	No modification is required.	No modification is required.
	Vertical Curvature	Meet or improve conditions that are typical on the remainder of the roadway.	No modification is required.	No modification is required.
	Horizontal Curvature	Meet or improve conditions that are typical on the remainder of the roadway.	No modification is required.	No modification is required.
	Minimum Super Elevation	Meet or improve conditions that are typical on the remainder of the roadway.	No modification is required.	No modification is required.
	Maximum Grade	Meet or improve conditions that are typical on the remainder of the roadway.	No modification is required.	No modification is required.
	Minimum structure width	The width must be 24 ft.	No modification is required.	This width can be reduced as CAVs need small width of the roadway comparing to the other vehicles.
	Bridge End Guard Fence	This fence should be at least up to transition section and end treatment point.	No modification is required.	No modification is required.

	Approach Roadway	1. For a minimum length of 50 ft, adjacent to the bridge end, the roadway crown should match clear width across structure (24 ft) plus additional width to accommodate approach guard fence. 2. An appropriate transition (minimum length 50 ft) to county road width should be made in the sections of approach roadway located at the federal project extremities. 3. If roadway surfacing is included, a minimum of 20 ft surfacing width should be used for the 50 ft roadway section adjacent to the bridge.	No modification is required.	The approach roadway length should be modified considering CAV behavior.
	Traffic Control	Traffic control devices should be in conformance with the TMUTCD and details should be included in the plans.	No modification is required. (However improved efficiency can be obtained if traffic signs are developed for V2I communication especially when CAV technology is introduced)	No modification is required. (However improved efficiency can be obtained if traffic signs are developed for V2I communication especially when CAV technology is introduced)
Texas Park and Wildlife Departure Project	The modification of Highway Operations	The current design standard of TPWD must be followed.	No modification is required.	No modification is required.

Section 7: Miscellaneous Design Elements

This chapter deals with the additional design elements which are not discussed in earlier chapters.

1. Longitudinal Barriers,
2. Fencing,
3. Pedestrian Separation,
4. Parking,
5. Rumble Strips,
6. Emergency Median Openings on Freeways, and
7. Minimum Designs for Truck and Bus Turns.

Most of the design elements discussed in this chapter are relevant to safety and are unaffected under mixed traffic conditions. Hence, the modifications proposed in Table 27 are strictly for areas where all the traffic is automated or dedicated AV lanes are provided. However, the elements which require modification under mixed traffic conditions are explicitly mentioned in their respective paragraphs.

Longitudinal Barriers and Roadside Safety Hardware Criteria

Concrete Barriers (Roadside and Medians)

One of the objectives of concrete barriers is to restrict unlawful turns/crossings from vehicles/pedestrians. AVs will likely be programmed to follow a specific path leading to the elimination of unlawful turns. The use of flush medians will also discourage the use of barriers. This will lead to a reduction in the requirement of concrete barriers in a controlled-access highway and urban roads having relatively narrow ROW. However, in places where there is large pedestrian movement, concrete barriers should be provided to prevent illegal crossings from pedestrians. Moreover, median, and roadside concrete barriers are required to prevent crossover crashes in the case of median barriers or as roadside containment of runaway vehicles in the case of bridges and overpasses.

Guardrail

Guardrails are protective devices that are designed to resist the impact of a vehicle leaving the highway inadvertently. Since AVs are equipped with ADAS: lane departure warning and lane-keeping assistance, they can follow the lane markings and commute from one place to another. This can lead to a reduction in the requirement of guardrails. However, in places where there is regular snowfall or the roadway is uphill, guardrails may be required as AVs might not be able to detect the lane markings properly which will require the human drivers to take over the vehicular control from AVs (level 3). Guardrails can also be incorporated with sensors which might come handy on adverse weather conditions. Prevention of out-of-control vehicles leaving the roadway alignment due to vehicle malfunctions such as blown tires may still be an issue with AVs.

Attenuators (Crash Cushions)

These are provided to prevent the impact of an errant vehicle on a fixed object. Some fixed objects cannot be moved, relocated, or made as breakaways; hence, attenuators are crucial. Although AVs can be programmed to traverse using a certain path (avoiding contact with fixed objects), ADS failure and ODD exit are omnipresent and cannot be neglected. Hence, crash cushions should also be provided for AVs to minimize the impact when automated system failure or ODD exit occurs, and the human driver takes over.

Roadside Safety Hardware Criteria

The safety performance of roadside hardware safety devices is assessed as per the guidelines provided by AASHTO Manual for Assessing Safety Hardware (MASH 2016). Tests are conducted for a small car (2420 lbs.) and a large pick-up (5000 lbs.) for low-speed (45 mph or less) and high-speed (50 mph or more) roadways. Similar tests need to be conducted for AVs as well to establish the roadside safety hardware criteria.

Fencing

Fencing is provided to prohibit unrestricted access to the through lanes by pedestrians, animals, and/or vehicles. Under AVs, these scenarios remain the same. Hence, no change in the existing design is recommended.

Pedestrian Separation and Ramps

The safety of pedestrians is of utmost importance while planning and designing pedestrian facilities (sidewalks, curb ramps, driveway crossings, etc.). The design considered should accommodate people of all ages and abilities, including people too young to drive, those who cannot drive, and those who choose not to drive.

As per the Federal Surface Transportation Law (23 U.S.C. 217(g)), the design of new and improved transportation facilities should accommodate bicyclists and pedestrians, including persons with disability. Moreover, in locations where pedestrian use is authorized, the design and alterations must follow the accessibility requirements established by the Americans with Disabilities Act (ADA) Standards (2010) adopted by the U.S. Department of Justice (DOJ), the ADA Standards (2006) adopted by the U.S. Department of Transportation (DOT), Proposed Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-way (PROWAG), and the Texas Accessibility Standards (TAS).

Major changes are not recommended regarding AVs because all the pedestrian facilities still need to be provided in order to ensure minimum contact between pedestrian and automobile traffic in the roadways. The various pedestrian facilities are discussed below:

Linear Pedestrian Facilities

Sidewalks and shared use paths (multi-use paths designed for use by bicyclists and pedestrians, including pedestrians with disabilities) should be designed as per the guidelines provided in Section 7.3.3 of TxDOT RDM on curbed and non-curbed roadways. Pick-off and drop-off points for AVs can also be integrated into the sidewalks provided they do not interfere with the accessibility and functionality of the sidewalks.

Curb Ramp

A curb ramp is a connection between sidewalks and street crossings. Special care should be given while allocating the locations for fixed objects (e.g., poles, signal cabinets, etc.), as they should not limit the access for pedestrians and bicyclists using sidewalks and curb ramps. Curb ramp is designed as per the current TxDOT Pedestrian Facility Standards and should be compliant with PROWAG. The design and use of the curb ramp remain the same in an automated environment.

Driveways

Driveways are one of the locations of potential conflict between pedestrians and vehicles. Hence, they should be designed to maximize visibility and minimize conflict between motorists and pedestrians. Adequate space along with proper signs and symbols may aid AVs to navigate the driveway crossing safely and soundly. A driveway should be designed as per the guidelines provided in the RDM.

Intersections and Crossings

Intersections are the major point of conflict between pedestrians and vehicles. Proper design of multimodal intersections ensures safety for all the users with effective and efficient traffic control measures. A key strategy is to reduce the vehicular speed at intersections which can be accompanied by several other strategies: eliminating free-flowing movements (truck apron), increasing visibility at the intersection (curb extension and parking restrictions near pedestrian crossings) and proper signalization strategies at locations with signals. Moreover, proper, and uniform lane markings and visible signs and symbols with adequate descriptions will most likely increase the performance and efficiency of AVs.

Overcrossings and Underpasses

Grade separated pedestrian facilities (overcrossings and underpasses) should be accessible, safe, and comfortable to use (good sight lines, and proper lighting wherever necessary). These facilities may come in handy in places of heavy pedestrian movements (e.g., an apartment complex across a shopping mall; a residential neighborhood near a busy street; a high-volume hiking trail). No changes are recommended regarding AVs because pedestrian separations still need to be provided on those locations.

Work Zone and Temporary Traffic Control Pedestrian Accommodations

The detour provided to assist pedestrians around the work zone using temporary walking paths by placing appropriate barricades, reflectorized drums, and signage should be readable and in the line of sight of the AVs.

Lighting

Proper pedestrian lighting provides safety to pedestrians as well as motorists. The illumination levels and uniformity for lighting in roadways, walkways, bicycle facilities, crosswalks, and pedestrian underpasses are designed as per the Federal Highway Administration (FHWA) standards. The quality and color temperature of light might impact the working of AVs.

On-Street Parking

For human-driven vehicles, parallel and perpendicular accessible parking should be provided following PROWAG's guidance on accessible parking spaces including the minimum number of accessible parking spaces required. In terms of AVs, this might change. The allocated space for on-street accessible parking near busy urban areas may be dieted due to the ADAS capabilities of AVs. Instead, provisions for accessible pick-up and drop-off points may be developed.

Transit Access

Like other pedestrian facilities, transit stops should also be accessible to all members of the public. It should be designed as per the guidelines given in Section 7.3.11 of TxDOT RDM and Section R308 of PROWAG. Boarding and alighting areas for transit stops should be well connected to the pick-up and drop-off points for AVs.

Micromobility Vehicles

Micromobility vehicles (bicycles, e-bikes, and e-scooters) are mostly provided in urban and suburban areas. They are either docked (parked in the right-of-way for pick-up and drop-off either at stations) or dockless (within a service area).
Parking of the micromobility vehicles may present a challenge. It may disrupt the movement of AVs if not properly managed. Coordination with local government and micromobility companies should be done to determine adequate locations for parking these vehicles. Proper surface marking and signage should be used and followed to distinguish the boundary and prevent the conflict of micromobility vehicles with AVs.

Parking

TxDOT's RDM discusses two types of parking:

Fringe Parking Lots

Fringe parking lots are the parking lots that are located at the fringe of an urban area where people gather, park their vehicles, and proceed to their destination (by carpooling, traveling in transit, or a combination of both). During the mixed traffic conditions or initial phase of automation (low ODD), AVs (both car and transit) and CAVs can be designed to operate on a fixed path (from fringe parking lots to a CBD). This will lead to a reduction in congestion. Hence, developing fringe parking lots having sufficient AV infrastructures (parking stations, pick-up and drop-off points, etc.) may lead to a smooth transition from manual to automated driving.

Parking Along Highways and Arterial Streets

As per TxDOT's RDM, parking along highways should only be permitted in emergency conditions, and when the speed and traffic volumes are below capacity. Shoulders are used for parking in those situations. This is due to the limited ROW in the urban and suburban streets. Reduction in the parking lot requirements is expected as the ADAS relevant to parking keeps on developing and the market penetration of AVs keep on growing. Design considerations regarding auto valet parking and drop-off and pick-up points along highways and arterial streets need to be considered in an automated environment.

Rumble Strips

As per the FHWA (*200*), rumple strips become "rumble stripes" when an edge line or a centerline pavement marking is placed on it. The marking will lead to increased visibility in dark and wet conditions. Hence, rumble stripes should be provided in roadways where visibility is poor.

Emergency Median Openings on Freeways

The current practice of providing emergency median openings with administrative approval when the distance between interchanges is large (greater than 3 miles) should still be followed under mixed traffic conditions. However, if dedicated AV lanes are provided, medians may not be required at all (or flush medians can be provided).

Minimum Designs for Truck and Bus Turns

No modifications are proposed regarding the minimum designs for truck and bus turns because the turning path and turning radius are dependent on the vehicular dimension of the design vehicle. Robust changes between the dimension of an AV and a human-driven vehicle are not expected.

Table 27 Miscellaneous design elements and the proposed modifications

Design Elements	Classification	Definitions	Existing Design Conditions	Modifications Proposed for Dedicated Lane/ Full Automation
Longitudinal Barriers and Roadside Safety Hardware Criteria	Concrete Barriers	To prevent illegal turns of vehicles and unlawful turns of medians by pedestrians.	1. Controlled access highway: generally provided in medians of 30 ft or less. 2. Non-controlled access highway: may be provided in medians of 30 ft or less. 3. On medians greater than 30 ft, concrete barriers can be provided based on operational analysis. At medians greater than 25 ft, cable median barriers can also be provided as per Appendix 2, chapter 8 in RDM.	The dependency on concrete barriers can be reduced. However, special consideration should be made in places where unlawful turns by pedestrians are existing.
	Guardrail	To resist the impact of the vehicle leaving the facility inadvertently and deflect it back to the roadway or slow down the vehicle to a complete stop.	1. Guardrail should be offset at least 4 ft and desirably 5 ft or more from the nearest edge of fixed objects. 2. At overpasses, guardrail should be anchored securely to the structure. 3. Standard height = 31 inches or 28 inches (see Appendix 2, section 3 in RDM)	Guardrails may not be required in places where AVs can follow the lane markings and adjust themselves in the roadways. However, in adverse weather conditions they might become handy.
	Attenuators	Provided at locations where fixed objects cannot be moved, relocated, or made breakaway, and cannot be adequately shielded by a longitudinal barrier. Commonly used in at exit ramp gore, and to shield bridge columns as well as	The type of attenuator to be used should be based on impact decelerations, redirection capabilities, anchorage and back-up structure requirements, debris produced by impact, and ease and cost of maintenance.	No modifications are proposed.

		roadside and median barrier terminals.		
	Roadside Safety Hardware Criteria	To provide guidance relevant to crash-test levels with specified vehicle, speed, and impact angle for each level.	Based on AASHTO Manual for Assessing Safety Hardware (MASH 2016).	Tests need to be conducted on AVs and new safety hardware criteria are to be established.
Fencing		To mark the legal boundaries of ROW and to prohibit unrestricted access to the through lanes by pedestrians, animals and/or vehicles	See Table 7-1 in TxDOT RDM.	Remains same.
Pedestrian Separation and Ramps	Linear Pedestrian Facilities	To provide an area for pedestrian travel separated from automobile traffic.	Guidelines provided in Section 7.3.3 of TxDOT RDM.	Pick-up and drop-off points can be connected to the sidewalks provided they do not interfere with the functionality of the sidewalks.
	Curb Ramp	To connect sidewalks and street crossings.	Based on TxDOT Pedestrian Facility Standards and PROWAG compliant.	Remains same.
	Driveways	A small private road connecting a public road to one or a small group of structures.	Guidelines provided in Section 7.3.5 of TxDOT RDM	Proper signage, symbols, and/or markings should be used to guide AVs.
	Intersections and Crossings	A major point of conflict between pedestrians and vehicles.	Various speed reduction techniques by eliminating free-flow movement (truck apron, raised crosswalks and intersections, etc.) and increasing visibility (curb extension and parking restrictions near pedestrian crossings). The design parameters of the above-mentioned techniques are discussed in their respective sections in RDM.	Uniform lane markings and visible signs and symbols with adequate descriptions will most likely increase the performance and efficiency of AVs.
	Overcrossings and Underpasses	To eliminate all at-grade pedestrian crossings.	1. Generally limited to controlled-access facilities. 2. On highways except for freeways, a pedestrian crossing is considered	No modifications are proposed.

			only in unusual conditions. However, pedestrian structures (underpass and overcrossing) may be used to provide for heavy pedestrian movements adjacent to factories, schools, parks, athletic fields, etc. 3. All separations provided must be accessible to the disabled unless alternate safe means are provided.	
	Work Zone and Temporary Traffic Control Pedestrian Accommodations	Construction activities that affect pedestrian facilities or connectivity to those facilities must provide and maintain an accessible detour.	Guidelines provided in Part 6 of the TMUTCD.	All the temporary means and tools used for pedestrian accommodations such as barricades, reflectorized drums, and signage should be noticeable and in the line of sight of AVs.
	Lighting	To provide safety to pedestrians as well as motorists.	Standards provided by FHWA.	The quality and color temperature of light might impact the working of AVs.
	On-Street Parking	Deals with parallel and perpendicular on-street accessible parking.	Guidelines provided by PROWAG.	The dimensions of the parking space may decrease. Provisions for accessible pick-up and drop-off lanes might need to be established.
	Transit Access	Transit stops must be accessible to all members of the traveling public. They should be well lit and highly visible to promote safety and comfort.	Guidelines provided in Section 7.3.11 of TxDOT RDM and Section R308 of PROWAG.	Accessible connection between the pick-up and drop-off points for AVs and boarding and alighting area for transit stops.
	Micro-mobility Vehicles	Small, fully, or partially human-powered vehicles such as bicycles, e-bikes, e-scooters. Either docked or dockless.	Coordination with the local government and micro-mobility companies to determine the sizes and locations of the device parking areas and proposed locations for	Parking of micro-mobility vehicles may pose a challenge on AVs. Proper surface marking and signage should be used and followed to distinguish the

			new docking stations for dockless and docked micro-mobility vehicles, respectively.	boundary and prevent the conflict of micro-mobility vehicles with AVs.
Parking	Fringe Parking Lots	To mitigate congestion and provide energy conservation measures.		Increase the number of fringe parking lots and provide AV infrastructures in the parking lots (charging stations, pick-up and drop-off zones, etc.).
	i) Park and Pool Lots	Located at the fringe of an urban area where a group of two or more drivers can gather, leave their vehicle, and proceed to a common destination in one of the group vehicles.	1. Located within highway ROW. 2. Is designed to accommodate passenger vehicle with respect to parking stall widths, drive through isles and turning movements.	
	ii) Park and Ride Lots	Located along express bus routes to attract automobiles from low-density suburban development.	1. While designing the lots, the time required to reach one's destination by bus (transit) must be comparable to or less than driving one's own car. 2. Maximum walking distance of 650 feet. 3. Provide bus loading and bus travel area.	
	iii) Combination Park and Pool/Park and Ride Lot	To serve the purposes and combine the features of both the facilities.		
	Parking Along Highways and Arterial Streets			AVs may reduce the requirements for parking provided along highways with increased market penetration. However, an escalation in the pick-up and drop-off points can be expected.

	i) Emergency Parking	To provide parking in emergency situations.	Shoulders of adequate design provide for this required parking space.	
	ii) Curb Parking	Should only be permitted when speed is low, and the traffic volumes are well below capacity.	When allowed, the width of the parking lane should be 10 feet and a minimum setback of 20 feet should be provided from the radius of the intersection.	
Rumble Strips		A cost-effective countermeasure to reduce the number and severity of roadway departure crashes.	Provided on roadways with a posted speed limit of more than 45 mph. Provided to alert the distracted or drowsy human drivers whenever they cross the edge or centerline.	The need for rumple strips may be redundant because AVs can be programmed to follow the lane markings. However, rumble stripes (rumple strips + markings) will increase visibility under dark and wet conditions which will be beneficial for AVs. Hence, rumble stripes should be provided in such roadways where visibility is a concern.
Emergency Median Openings on Freeways		Generally provided in rural areas under administrative approval when the distance between interchanges is large.	Not provided in urban locations and provided in rural areas where more than minimum sight distance is available (See Chapter 7, Section 6 and Appendix 2, Section 9 in RDM.	Medians might be reduced to a minimum or might not be required at all.
Minimum Designs for Trucks and Bus Turns		The principal dimensions affecting turning paths and turning radii depend upon the minimum centerline turning radius, the out-to-out track width, the wheelbase, and the path of the inner rear tire.	See Table 7-2 and Figure 7-46 in TxDOT RDM	Remains same due to similar vehicular dimensions of AVs and human-driven vehicles.

Section 8: Mobility Corridor (5 R) Design Criteria

Mobility corridors are the corridors that are designed and intended for long-distance controlled access high-speed travel. The design speeds of these corridors range between 85 mph to 100 mph. Whenever possible, these corridors should be designed to accommodate a 100 mph design vehicle to maximize their future potential keeping in mind the social, economic, and environmental impacts. The design elements discussed in this section are:

1. Roadway Design Criteria,
2. Roadside Design Criteria, and
3. Ramps and Direct Connections.

If dedicated lanes are provided for AVs, setting higher speed limits for those lanes may enhance the performance of the lanes (*201*). However, higher speed is likely to cause more crashes and fatalities. AVs can perform better and enhance network efficiency by increasing the traffic throughput if dedicated AV lanes are provided. But, improvements in traffic throughput are noticeable only at higher market penetration of AVs (*95, 201, 202*). To overcome the limitation of lower market penetration of AVs/CAVs, dedicated lanes can be shared by CAVs and HOVs at lower market penetration of CAVs to increase the overall network mobility (*203*). Therefore, speed improvement in the traffic can be anticipated only once the market penetration of AV reaches 100%.

Providing AV dedicated lanes for the mobility corridor also enhances the platooning phenomenon. AVs can communicate better with each other than with a human-driven vehicle. Platooning will lead to a reduced time gap and increased lane capacity. Hence, platooning may lead to a smaller width and decreased number of lanes required to move the same traffic volume. However, before platooning, studies relevant to pavement rutting need to be done for heavy AVs.

The design elements mentioned in this section have been previously discussed in Sections 2 and 3 for design speeds ranging up to 80 mph. Therefore, no definitions are provided for the various design elements discussed in this section, and only the proposed modifications under mixed traffic conditions and dedicated AV lanes are discussed as highlighted in Table 28.

Roadway Design Criteria

Lane Width and Number

Under mixed traffic conditions, lane width and number may remain the same because the interaction between AVs and human-driven vehicles in a high-speed highway may cause disengagement among AVs and lead to difficulty in implementing CACC. In the case of dedicated AV lanes, lane width and number can be reduced provided the successful implementation of various ADAS in the case of automated cars. Space that becomes available due to the road diet can be used to promote various curbside activities and safer pedestrian/bike friendly streets as mentioned in section 2.

Shoulders

A shoulder width of 12 ft should be enough for both mixed traffic conditions and dedicated AV lanes. Shoulders can be used as a safe place to stop or restart a vehicle (manual driven or AV) in an emergency, or when reaching the exit of an ODD, or performing safety maneuvers when automation fails.

Pavement Cross Slope

Special care should be given to pavement cross slope as stagnation of water in the pavement may lead to the unstable performance of AVs.

Vertical Clearances at Structures

No modifications are required both in terms of mixed traffic conditions and dedicated AV lanes as vertical clearances depend upon the design vehicle's height.

Stopping Sight Distance

For mixed traffic, due to the presence of human drivers in the roadway, conventional values of SSD are to be followed. For dedicated AV lanes, SSD could reduce due to the improved reaction time of AVs when an obstacle is encountered.

Grades

Passenger vehicles are not affected by grades as steep as three percent. However, depending on the length of grades, a slope of even two percent may affect trucks. Therefore, truck traffic should be given priority while designing the grades along the mobility corridor. Under mixed traffic, the length and rate of the grades must be limited to as low as possible to avoid undesirable speed differentials. For AV dedicated lanes, the speed differentials can be kept under control. Hence, steeper grades can be achieved. However, grades are controlled by the ability of the design vehicle to climb the slopes. And large vehicles may slow down considerably on steep grades creating a traffic problem even for AVs.

Curve Radii

No modifications are proposed as the minimum radii of a curve depends upon the superelevation rate and friction factor as well as the design vehicle dimensions. However, provide a larger radius whenever enough ROW is available.

Superelevation

No modifications are proposed because the maximum superelevation that can be provided remains the same. While providing superelevation, drainage criteria must also be fulfilled.

Vertical Curves

For a mobility corridor, the design consideration of vertical curves remains the same as that of designing for a normal roadway. For mixed traffic, no modifications are proposed due to the presence of human drivers. And for dedicated AV lanes, a decrease in the length of sag and crest vertical curves is expected.

Roadside Design Criteria

Clear Zones

The clear zones recommended in Table 8-10 of the RDM may be enough for both mixed traffic and dedicated lane conditions.

Slopes

The side slopes provided should be as flat as possible to aid the out-of-control vehicle to recover or make a controlled deceleration. The values recommended in Table 8-11 of the RDM can be followed under mixed traffic as well as dedicated AV lanes.

Medians

For mixed traffic, provide median barriers whenever required as per Table 8-10 of the RDM. For dedicated AV lanes, AVs traffic can stay in their direction of flow due to various ADAS capabilities. However, due to the risk of head-on collision, the width of the medians must be maintained. Moreover, the median can also be integrated with sensors that aid the smooth operation of AVs.

Ramps and Direct Connections

Design Speed

The design speed of a ramp is based on the relationship between the ramp design speed and the mainlane design speed. Currently, the ramp design speed is taken as 85 or 70 percent of the mainlane design speed. It is also imperative to limit the speed differential between the design speeds of the main lane and the ramp. Table 8-12 of the RDM provides the design speed of the ramp in relation to the mainlane design speed. No modifications are proposed to prevent the escalation of the speed differential which can negatively impact traffic safety.

Lane and Shoulder Widths

For AV dedicated ramp, lane and shoulder widths can be reduced due to various ADAS capabilities of AVs. In case of mixed traffic, the lane and shoulder widths are recommended to be provided concerning the human drivers.

Acceleration and Deceleration Lengths

AVs can communicate with themselves and can accelerate and decelerate quicker in a more precise manner. However, the lengths ultimately depend on the passenger’s comfort. Further, under mixed traffic conditions, the acceleration and deceleration lengths are recommended to be provided concerning the human drivers.

Distance Between Successive Ramps

The merge, diverge, and weaving operations that take place between ramps are used to determine the distance between successive ramps. In dedicated lanes, AVs can communicate with each other and adjust their position, velocity, acceleration, and deceleration which will lead to smoother merge, diverge, and weaving operations (*204*).

Grades and Profiles

Grades and profiles depend on the design speed selected for the ramp. Hence, no modifications are proposed since the design speed (Table 8-12 of the RDM) is recommended to remain the same.

Cross Section and Cross Slopes

For both the mixed traffic and AV dedicated lane, the cross slope should be inclined in the same direction as the main lanes of the roadways. Cross slope provided will be dependent on the pavement used and drainage considerations.

Table 28 Mobility corridor and the proposed modifications

Design Elements	Classification	Existing Design Conditions	Modifications Proposed	
			Mixed Traffic	**Dedicated Lane**
Roadway Design Criteria	Lane Width and Number	Minimum lane width = 13 ft Number of lanes = as per the level of service evaluation	Remains same as interactions between human-driven vehicles and AVs on high-speed corridors may lead to larger lane width	Minimum lane width can be reduced since AVs can travel in a shorter width due to various ADAS
	Shoulders	Minimum width of inside and outside shoulders = 12 ft	Remains same since 12 ft shoulders should be enough to temporarily contain the vehicles (AVs/Non-AVs) if any failure occurs	Remains same since 12 ft shoulders should be enough to achieve minimal risk condition when an AV encounters ADS failure or exit of its ODD
	Pavement Cross Slope	Recommended cross slope = 2 percent	Remains same	Remains same. However, it is highly recommended to have slopes that prevent stagnation of water.
	Vertical Clearances at Structures	i) All controlled access highways = 16.5 ft ii) Freight network (freeways) = 18.5 ft iii) Pedestrian crossover structures = 1 ft greater than that provided for other grade separation structures	No modifications are proposed as the design condition depends on the design vehicle's height	No modifications are proposed as the design condition depends on the design vehicle's height
	Stopping Sight Distance	Based on reaction time, design speed, and deceleration rate of design vehicle (see Table 8-1 in RDM for specific values at various design speeds)	Remains same as the roadway will be shared by AVs and HDVs	Can be reduced based on the improved reaction time of AVs
	Grades	As per Table 8-2 in the RDM	Remains same	Steeper grades can be achieved. However, grades are controlled by the ability of the design vehicle to climb the slopes. Moreover, large vehicles may slow down considerably on steep grades creating a traffic problem.

	Curve Radii	Radius is calculated based on design speed, superelevation rate, and friction factor (see Table 8-3 in RDM for specific values of minimum radius under different scenarios)	No modifications are proposed since vehicle dimensions may not be altered under vehicle automation	No modifications are proposed since vehicle dimensions may not be altered under vehicle automation
	Superelevation	See Tables 8-6 and 8-7 in the RDM for values of superelevation for various design speeds and radii	Superelevation depends upon radius and friction factor, which remains the same. Hence, no modifications are proposed.	Superelevation depends upon radius and friction factor, which remains the same. Hence, no modifications are proposed. However, in places where superelevation is low or zero, drainage becomes important to avoid waterlogging that affects ODD.
	Vertical Curves	Depends on the available sight distance (see Table 8-9 in the RDM)	Remains same since the design will be based on human-driven vehicles	Improved sight distances and replacement of headlight height by the height of sensors provide scope for reduced length of the vertical curve
Roadside Design Criteria	Clear Zone	As per Table 8-10 in the RDM	The clear zone requirements mentioned in Table 8-10 should be sufficient for mixed traffic. Hence, no modifications are required.	The clear zone requirements mentioned in Table 8-10 should be sufficient for AV dedicated lanes as well. Hence, no modifications are required.
	Side Slopes	As per Table 8-11 in the RDM	The side slopes proposed in Table 8-11 should be sufficient for mixed traffic. Hence, no modifications are required.	The side slopes proposed in Table 8-11 should be sufficient for AV dedicated lanes as well. Hence, no modifications are required.
	Medians	Median barriers should be considered when the median widths are less than those shown in Table 8-10 of the RDM	Remains same	Medians may be provided with sensors that aid AV operation. The width of the median and the design criteria for median barriers are

				recommended to remain the same.
Ramps and Direct Connections	Design Speed	Depends on the design speed of the mainlane and limiting values of speed differentials among the ramp design speed and mainlane design speed	No modifications are proposed to preserve the speed differentials	No modifications are proposed because it is anticipated that it can escalate the speed differentials which can compromise traffic safety.
	Lane and Shoulder Widths	As per Table 8-13 in the RDM	No modifications are proposed as interactions between HDVs and AVs on ramp may lead to larger lane and shoulder width	Minimum lane and shoulder widths can be reduced since AVs can travel in a shorter width due to various ADAS
	Acceleration and Deceleration Lengths	As per Tables 8-14 and 8-15 in the RDM	Remains same	Lengths can be reduced since AVs can communicate with each other and adjust their speed accordingly. However, the lengths ultimately depend on the passenger's comfort.
	Distance Between Successive Ramps	Designed as per Highway Capacity Manual based upon the merge, diverge, and weaving operations that take place between ramps	Remains same	No modifications are proposed. However, AVs may have better and smoother merge, diverge, and weaving operations between ramps
	Grades and Profiles	Design speed selected for the ramp	Remains same	Remains same
	Cross Section and Cross Slopes	Based on the pavement used and drainage considerations	Remains same	Remains same

CHAPTER 4: AVS ADOPTION SCENARIOS

AVs technology attracted immense recognition recently that there has been a vast ongoing assessment of the factors that influence their adoption. Analysis of market penetration is beneficial in creating economic forecasts that are relevant to auto and other supporting industries. In addition, understanding the market penetration of AV will enable planners in making decisions for infrastructure needs for CAVs. The tangible impact of AVs is expected to be decided by a combination of multiple factors and the market penetration of AVs is one of the primary ones. Other important factors include the pervasiveness of ride-share systems, residential and car-ownership choices, trip making, route choice behavior, and the impact of CAVs on capacity. AVs are targeted to make travel ever so convenient and safer by taking the human element out of the loop and relying all on the vehicle to navigate itself through traffic. The high cost of purchasing an AV combined with the low cost of operation makes AVs more suitable for use in ride-hailing than for ownership. The low cost and reliability of using AV based ride-hailing services will increase the mobility and impact the way people make travel decision. Information regarding travel times and road conditions gathered and shared by CVs will make it easier for individuals or algorithms in routing systems to make optimal decisions regarding route choice (*205*). AVs will increase mobility for groups who are currently unable to operate vehicles, for example, young children, elderly people, and physically challenged individuals.

When analyzing the system of AVs three characteristics can be identified about this technology. First, the technology is uncertain due to a lack of data in the literature. There is still a lot of unknowns concerning the factors that influence the development and diffusion of AVs. A second characteristic is that the factors in the system of AVs are very interrelated. For instance, congestion has an impact on travel behavior, which in its turn has an impact on the usage of AVs. The factors that affect the diffusion or adoption rate are part of the system of AVs. While quantifying the market development and diffusion of AVs, researchers and experts have identified and emphasized various feedback loops that make the system complex. A multitude of these endogenous factors makes the behavior of the system unpredictable and dynamic (*206*). Past studies on vehicle safety systems and vehicle automation point out the significance of understanding consumer perceptions, attitudes, and experiences regarding related systems. Studies have also debated several different individuals and socio-demographic traits that could influence acceptance. The attitude of the consumer was found to be one of the most critical components in explaining the acceptance of AVs and CAVs. Consequently, numerous studies have incorporated the attitude of consumers in determining the AVs adoption. The ADAS and autonomous driving component market is driven by the increasing technological developments and advancements in ADAS systems, rising developments in connected infrastructure and ITS, demand for ADAS features in commercial vehicles, and growing concerns and measures over road safety. However, reliability issues, rising cyber threats in autonomous vehicles, high cost associated with LiDARs, and lack of government rules and regulations in developing regions, are some of the identified factors limiting the market growth (*207*–*209*). A list of general growth factors and resistance factors are listed below,

Growth factors:

- Expanding R&D activities in the domain of self-driving vehicles technology,

- Growing investment in Auto-Tech,
- Advancement in LiDAR technology,
- Impact of 5G Technology Enhancing Autonomous Driving Components,
- Widespread adoption of ADAS platform,
- Increasing Adoption of Autonomous Vehicles in Shared Mobility,
- Rising Focus Toward Vehicle Platooning, and
- Supportive government initiatives and efforts.

Pitfalls & Challenge:

- High cost,
- Security, safety, and reliability,
- Lack of infrastructure,
- Considerable gap in the existing AV regulations, and
- Lack of standardization in the traffic control devices and pavement markings.

Various techniques to Model AV Market Share

Disaggregate Model (Discrete Choice Model)

One of the major challenges while predicting AV market share is to monitor and track individuals' reactions and intentions towards using AVs (*210*). A disaggregate model is used to predict the market share of AVs at an individual level. One of the disaggregate models is the discrete choice model which explains and predicts an outcome based on a set of two or more discrete alternatives. Discrete choice models are based on rational choice; that is, when people are given a set of discrete alternatives, they choose the one which maximizes their benefit or utility (*211*). Various studies in the past have used discrete choice models based on vehicle ownership (*212*, *213*), household income (*212*, *214*), exposure to in-vehicle tech (*215*), travel time (*214*, *216*), residential condition (*217*, *218*). Golbabaei et al. (*210*) summarize the various predictors (demographic, psychological, and mobility behavior characteristics) that can influence user acceptance and adoption preferences and conclude that the early adopters of AVs will likely be males, young people, highly educated, having higher incomes and larger households, and living in a dense neighborhood.

Aggregate Model (Diffusion Model)

The Theory of Diffusion of Innovation, developed by Rogers (*219*), investigated the potential to adopt any innovative product based on the concept of relative advantage, compatibility, and complexity. The first concept, relative advantage, determines the edge a new technology/product has over the existing technology/product that is going to be replaced. Then the second concept namely, compatibility is used to measure the degree to which the new technology is aligned with an individual's need. The greater the compatibility higher is the likelihood of adoption. The third concept complexity measures the efforts required in adopting the new technology. In other words, it is the measure of the degree of ease with which the idea/technology can be implemented. Further, Rogers categorized the consumers into five groups or categories. These groups are innovators, early adopters, early majority, late majority, and laggards. Innovators although very low in percentage are the ones who influence early adopters. Early adopters are the group where the majority of opinion leaders are present. The early adopter group is the most significant in scaling up an innovation. This is because most of the consumers in the system are not equipped with the recent information and hence tend to follow the leaders (predominantly present in the early adopter's group). Hence as per Rogers, this group is the most critical group which can rapidly diffuse the product into the market and have the potential to make it an essential commodity in an individual's day-to-day life. Moreover, the non-cumulative diffusion will resemble a normal distribution with time and the cumulative diffusion will form a S-shaped curve as shown in Figures 36 and 37, respectively.

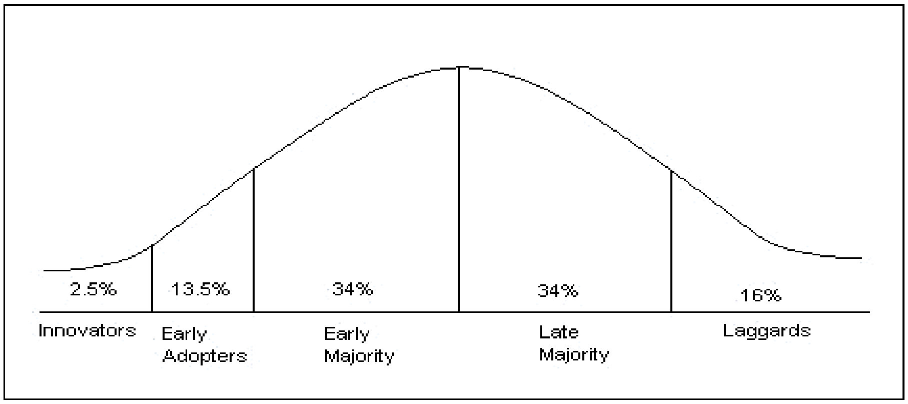


Figure 36 Non-cumulative diffusion curve

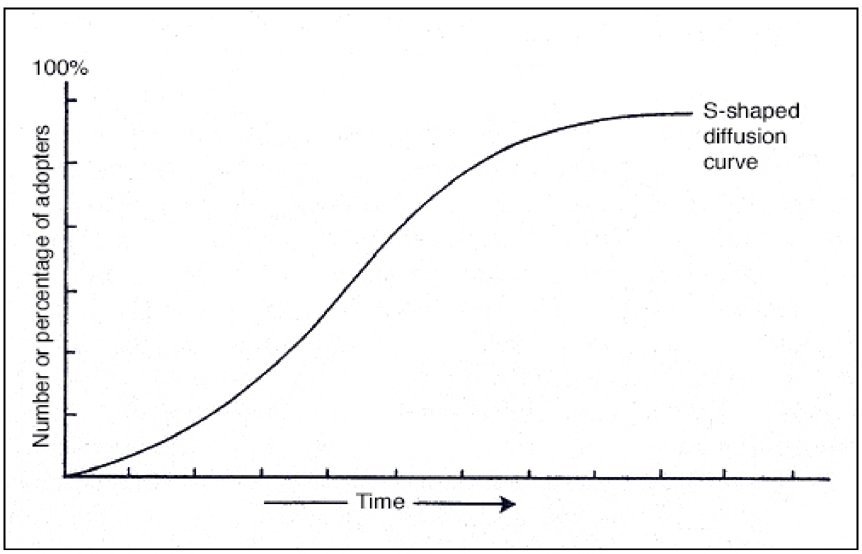


Figure 37 Cumulative diffusion curve

Bass Diffusion Model

Bass diffusion model is one of the most popular and widely accepted diffusion models. It is used in forecasting the diffusion of new products and technologies using innovation and imitation factors. This model relates the interaction among current adopters and potential adopters of a new product (*220*). Adopters are classified as innovators or imitators; thereby reducing the complexity of the theory of diffusion of innovation. Innovators are influenced by external factors (such as mass media communication) and are present at every stage of the diffusion process. Whereas imitators are influenced by internal factors (word-of-mouth) and satisfaction among the adopters. Figure 38 shows the non-cumulative temporal adoption of innovators and imitators (*221*).

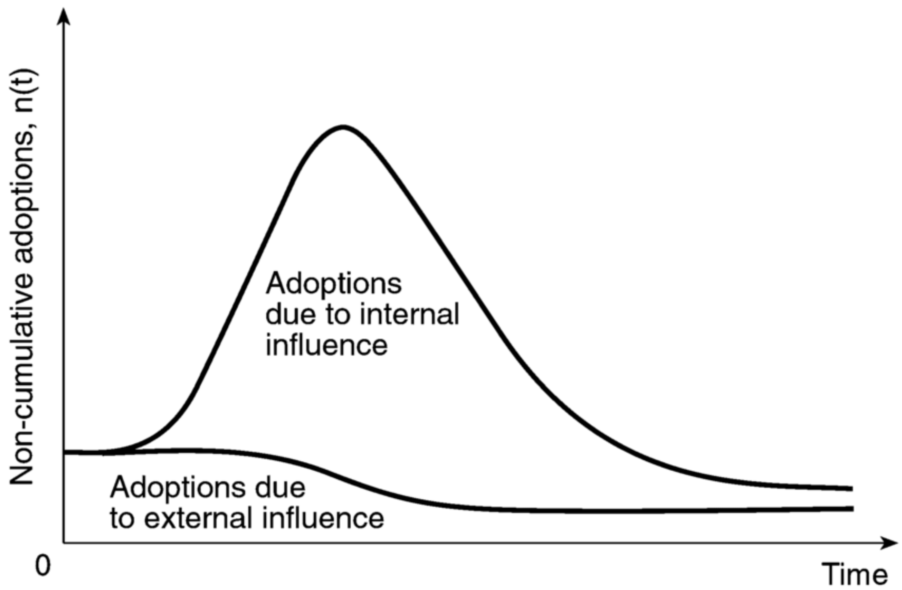


Figure 38 Adoptions due to external and internal influences in the Bass model. Source: Kale and Arditi (*222*)

Mathematically Bass model can be written as (*223*),

$$N(t) = M \frac{1 - e^{-t(p+q)}}{1 + (\frac{q}{p})e^{-t(p+q)}}$$

Where,
N (t): Cumulative adoption of AVs at time t.
t: Time period.
M: Maximum potential adopters.
p: Coefficient of innovation.
q: Coefficient of imitation.

Technology forecasting by Analogy

The future of technology development is critical in technology planning. It is required to allocate resources more efficiently. However, due to the characteristics of new technology, historical data of analogous entities can be leveraged to expose and describe the new technology development pattern, to characterize it more precisely, and to maximize gains or minimize loss from future conditions/scenarios (*224*).

The Bass model is a good foundation point for forecasting the long-term penetration pattern of new technologies and products under two types of conditions (*225*, *226*):

1. a product has recently been introduced and the penetration has been observed for a few time periods, or
2. the product has not yet been introduced, but it is similar in some way to existing products or technologies with a known diffusion history.

These conditions are required to estimate the unknown coefficients in the Bass model. Historical data must be available for at least four periods to allow estimation of p and q. If no such data is available, parameters estimated for historical innovations that are like the innovation being studied are often used instead (*225–227*). The Bass model has been widely employed in studies related to new technologies, particularly those in the automobile industry. Several studies have been conducted in the last few years to predict AV adoption rate. Litman (2014) (*228*) forecasted the implementation of AVs based on previous vehicle-related technologies (automatic transmission, air bags, hybrid vehicles, subscription vehicle services, and vehicle navigation systems) and fleet turnover rates. The study predicted that AVs would be on streets with high initial costs in the 2020s, and it would take up to 2050s to reach 80- 100% market share. Fagnant and Kockelman (*229*) projected a sooner mass-market presentation start for autonomous vehicles, considering that Nissan and Volvo announce their commercially viable autonomous vehicles in 2020 and it takes five years for price dropdown.

Parameters of Bass Diffusion Model

- Coefficient of innovation (p): This parameter captures a group of consumers who purchase the products due to external influences (such as advertisement, marketing, etc.). These types of consumers make their purchase decision independent of other consumers. The driving needs of innovators are easily met by an affordable, and reliable AV system (*230*).
- Coefficient of imitation (q): This parameter captures those consumers whose purchasing decisions are dependent on others. These adopters are also termed word-of-mouth consumers as their decision of buying a product is based on internal factors as well as customer satisfaction amongst the innovators (*230*).
- Market potential (m): This parameter specifies the potential number of adopters of a new product. Usually, the value of m is attained through the relevant historical data or expert opinion survey in the absence of historical data.

Bass parameters for passenger cars: Different values of p and q have been used in the past while forecasting the market potential of a new product or technology. Past researchers have used the historical sales data for HEV, PHEV sales data to estimate the market penetration of AVs assuming similar technology development rates (*226*). The foundational idea is that as the first years of HEV deployment have seen conservative and skeptical user adoption, a similar trend can be expected for AV adoptions. The study also considered the internet, and cellphone adoption and adjusted the diffusion model to overcome the limitations that HEVs would not be as revolutionary as AVs in changing the way people travel. Internet and cellphone usage are considered two revolutionary forces in the history of communications, similar analogy can be expected for AV in the automobile industry. Figure 39 illustrates the variation in the adoption rates for AVs using calibrated p, q values from existing literature. The forecasted AV adoption rates using technology analogy of electric by Lavasani et al. (*226*) was comparable to that of Litman's work (*228*), which predicted 80-100% of AVs sales in 2050s. The rate of adoption/sales of AVs was forecasted leveraging the technology analogy-based Bass diffusion models, using p, q evaluated by past researchers as illustrated in Table 29 and Figure 39.

Table 29 Bass model parameters for EVs, HEVs, CVs

Source	Technology	Innovation coefficient (p)	Imitation coefficient (q)
Massiani and Gohs (2015) ***(231)***	EV	0.0019	1.2513
Jensen *et* al. (2016) ***(232)***	EV	0.002	0.23
MacManus and Senter (2009) ***(233)***	EV	0.0026	0.709
Becker, Sidhu et al. (2009) ***(230)***	EV	0.01, 0.02 or 0.025	0.4
Gross (2008) ***(234)***	EV, HEV	0.01	0.1
Cordill (2012) ***(235)***	Toyota Prius	0.0016	1.45
	Hybrid Civic	0.00343	0.631
	Ford Escape	0.036	0.432
Steffens (2003) ***(236)***	Conventional cars	0.0076	0.0905
Shoemaker (2012)* ***(237)***	Pass. veh	0.0912	0.4692
	Utility veh	0.008124	0.4632
Lamberson (2008)* ***(238)***	HEV	0.000618	0.8736
Park et al (2011) ***(239)***	HEV	0.0037	0.3454
Jensen et al. (2014) ***(232)***	EV	0.002	0.23
Cao (2004) ***(240)***	HEV	0.000446	0.4788

Note: * Parameters estimated based on monthly data were annualized by multiplication with factor 12

Source: Massiani and Gohs (*231*), Simpson et al. (*241*)

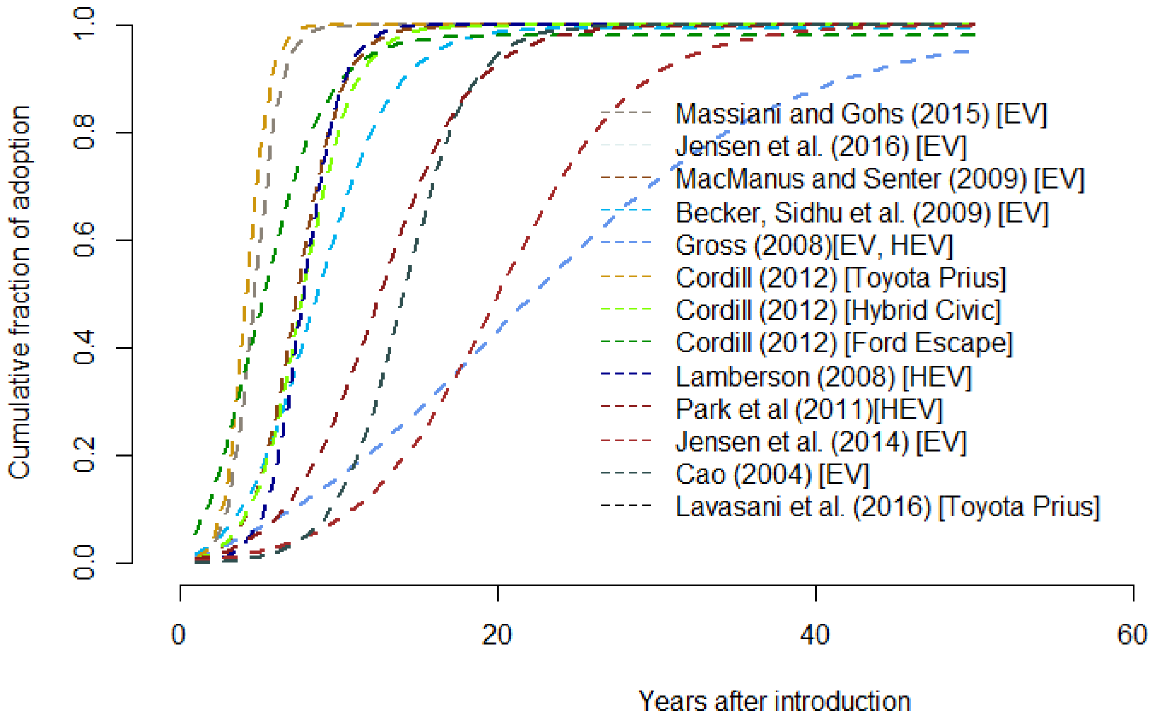


Figure 39 AV adoption forecast rates

Bass Model Parameters Calibration

As mentioned in the previous section, the parameters of Bass Diffusion Models are generally estimated:

1. by analogy to the histories of similar new products introduced in the past
2. by early sales returns as the new product enters the market
3. expert opinions

The market share of AV was forecasted using the EV sales data of the United States applying diffusion analogy and Bass diffusion model. Nine years of annual sales data of PEVs and PHEVs in the United States, as shown in Figure 40, was used for the calibration of the Bass model parameters. Market potential of the technology is extremely crucial for calibration of innovation and imitation coefficient in the Bass models. Numerous factors interplay and influence the market potential and consequently the Bass parameters p and q, including the attitude and taste of consumers that can vary across time and space. The total household units and the annual passenger car registration data (*242*) of the United States were considered for the initial values of the market potential for the estimation of AV diffusion. Non-linear regression was used to calibrate the Bass parameters. The estimates forecasted 100 percent saturation by 2035-2040, which seems too premature. The calibrated parameters p, q from the Bass model analysis using the total sales of PEVs and PHEVs are shown in Table 30.

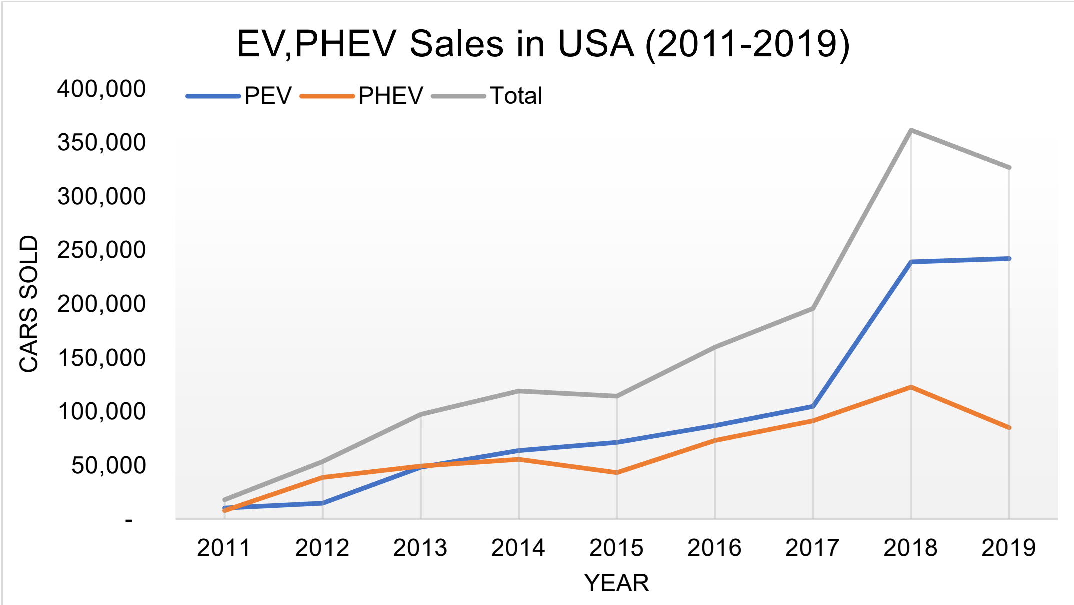


Figure 40 PEV, PHEV sales data

Table 30 Calibrated values of p and q

Parameters	Estimate	Std. Error Pr(>|t|)	t value
Coefficient of Innovation (p)	0.0054	2.215	0.0687
Coefficient of Imitation (q)	0.3735	2.863	0.0287

A significant technological transformation occurred in information and communication technology during the past 5 to 10 years. As of 2019, around 86 percent of total U.S. households reported having some form of internet subscription (*243*). Most Americans, around 96%, now own a cellphone of some kind. The share of Americans that own smartphones are now 81%, up from just 35% in Pew Research Center's first survey of smartphone ownership conducted in 2011. Along with mobile phones, Americans own a range of other information devices. Nearly three-quarters of U.S. adults now own desktop or laptop computers, while approximately half now own tablet computers and around half own e-reader devices (*244*). This implies that the diffusion parameters would have significantly changed over the past decade based on the influence of the user's AV adoption behavior and technology awareness/savviness. Large variation in the forecasts using technology analogy-based diffusion models as illustrated in previous section (Figure 39), further justifies the complexity and uncertainty involved in the market analysis of AVs, though Bass models are well known for fitting the adoption rates with minimum external influences. Additionally, as discussed in the beginning, factors that affect the diffusion or adoption rate are part of the system of AVs and quantifying the market development and diffusion of AVs, involves various feedback loops that make the system complex, and the endogenous factors make the behavior of the system unpredictable and dynamic (*206*).

Bass parameters for freight: Among all the sectors, the freight sector is expected to gain the highest benefits with the adoption of AV technology in its routine operations. The existing freight community is experiencing a growing shortage in the number of drivers and it is perceived that autonomous trucks could be the solution (*171*). Further, autonomous technology is expected to reduce fuel consumption by 10 – 15 %. Moreover, there has been growing research over a decade to identify the tendency of the freight organizations inclining towards fuel-efficient technology. Beginning from the year 2012 the North American Council for Freight Efficiency (NACFE) has been studying the inclination of freight organizations towards these fuel-efficient technologies. In its eighth update, NACFE investigated the adoption of various emerging technologies among 21 major North American fleets (*245*). Overall, 85 technologies were studied, categorized as practices, tractor aerodynamics, powertrain, tires/rolling resistance, idle reduction, trailer aerodynamics, chassis. Relying on the NACFE report published in 2015, Simpson et.al (*241*) investigated the connected autonomous truck adoption by various fleets in Shelby county, Tennessee. The observed Bass parameters in that study are presented in Table 31.

Table 31 Bass model parameters for freights

Technology Category	CoN (p)	CoM (q)	Adj. *R square*
Trailer Aerodynamics	0.0043	0.1927	0.951
Idle Reduction	0.0122	0.0984	0.875
Chassis	0.0000	0.1300	0.889
Tires/Wheels	0.0038	0.1605	0.931
Powertrain	0.0167	0.0927	0.929
Tractor Aerodynamics	0.0713	0.0996	0.847
Practices	0.0000	0.1084	0.834
Average:	0.0155	0.1261	0.894

Source: Simpson et al. (*241*)

Adoption Predictions for Freights

Considering the uncertainty surrounding the adoption models, priority has been given to well-established studies in identifying the adoption patterns of freight. Further, it must be noted that unlike passenger cars freight operations are mostly characterized by long-distance travels. Often, the road infrastructure accessed is not usually originated within the state. Therefore, it is rationale to determine the adoption patterns at an organizational level rather than a state level. Hence an approach similar to Simpson et.al (*241*) has been followed to evaluate the adoption trend in freight organizations. Unsurprisingly, the Bass parameter p was high for freight as compared to passenger cars since freight organizations are expected to show greater interest in vehicle automation. It was identified that complete automation would be achieved by the year 2080 as shown in Figure 41. Moreover, peak adoption rates in the freight industry are expected to attain in the year 2036. It is worth noting that the results correspond only to the freight organizations that are studied in the NACFE report (*245*). Therefore, a sensitivity analysis is performed to accommodate for higher market potential values. Results revealed that the adoption characteristics nevertheless remain the same, and the saturation year is not altered as observed in Figure 42.

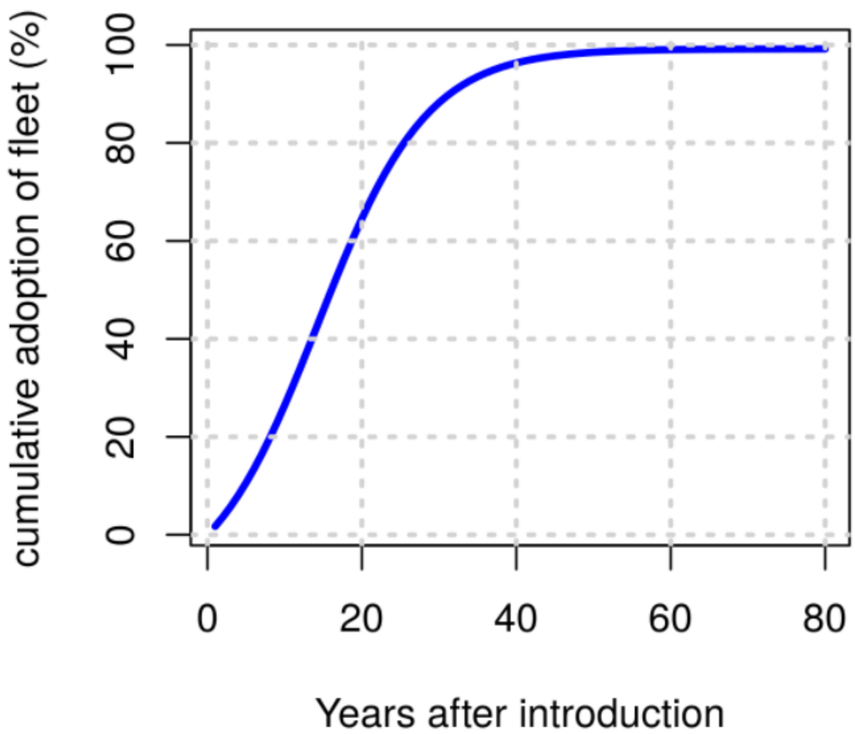


Figure 41 Cumulative distribution of AVs in freight

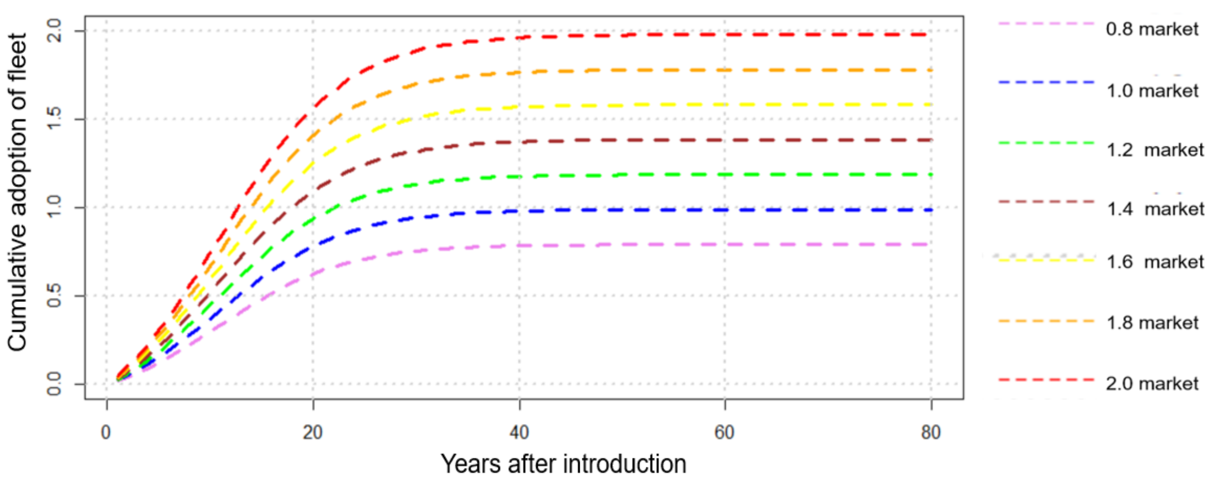


Figure 42 Sensitivity analysis of cumulative adoption of fleet with respect to market size

Clustering- Spatial Transferability of Existing Models

Substantial research has been done in the past to determine the imminent AV penetration and market scenarios and the consequential impact on the transportation system. However, very few studies focused on comprehending the segregation of levels at each stage of penetration. Center for Transportation Research (CTR) has performed an extensive study in understanding the current state of connected and autonomous vehicles (*205*). Similarly, Bansal and Kockelman (*246*) developed various scenarios to forecast the long-term adoption of AVs. Hence, an attempt has been made to utilize the existing results into the current study. To illustrate the spatial transferability of existing models, a clustering framework was used to group the 254 counties in Texas with respect to traffic (Vehicle Miles Travelled (VMT), considering both passenger car and freight), transportation infrastructure, safety, and socio-demographic and economic attributes. Precisely, a data driven Principal (PCA) based cluster analysis using Texas counties data was conducted to identify natural group based on similarity in the attributes using hierarchical clustering tools (*247*). The clustering framework is shown in Figure 43. Given a set of N items to be clustered, and an NxN distance (or similarity) matrix, the basic process of hierarchical clustering consists of the following steps (*248*):

1. Assign each item to its own cluster, so that if you have N items, you now have N clusters, each containing just one item. Let the distances (similarities) between the clusters equal the distances (similarities) between the items they contain.
2. Find the closest (most similar) pair of clusters and merge them into a single cluster, so that now you have one less cluster.
3. Compute distances (similarities) between the new cluster and each of the old clusters.
4. Repeat steps 2 and 3 until all items are clustered into a single cluster of size N.

In Steps 2 and 3, the algorithm deals with finding distances, which represents the similarity/dissimilarities, between cluster pairs. So, prior to clustering, it is required to determine the distance matrix that specifies the distance between each data point using some distance function. Euclidean distance (equation 1) was considered for the similarity measurement and Ward's minimum variance was used for the clustering or linkage criteria (equation 2).

$$d_{euc}(x, y) = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2} \quad (1)$$

$$\Delta(A,B) = \sum_{i \in A \cup B} \|\vec{x}_i - \vec{m}_{A \cup B}\|^2 - \sum_{i \in A} \|\vec{x}_i - \vec{m}_A\|^2 - \sum_{i \in B} \|\vec{x}_i - \vec{m}_B\|^2 \quad (2)$$

$$\text{Or, } \Delta(A,B) = \frac{n_A n_B}{n_A + n_B} \|\vec{m_A} - \vec{m_B}\|^2 \quad (3)$$

where m_j is the center of cluster j, and n_j is the number of points in it. Δ is called the merging cost of combining the clusters A and B.

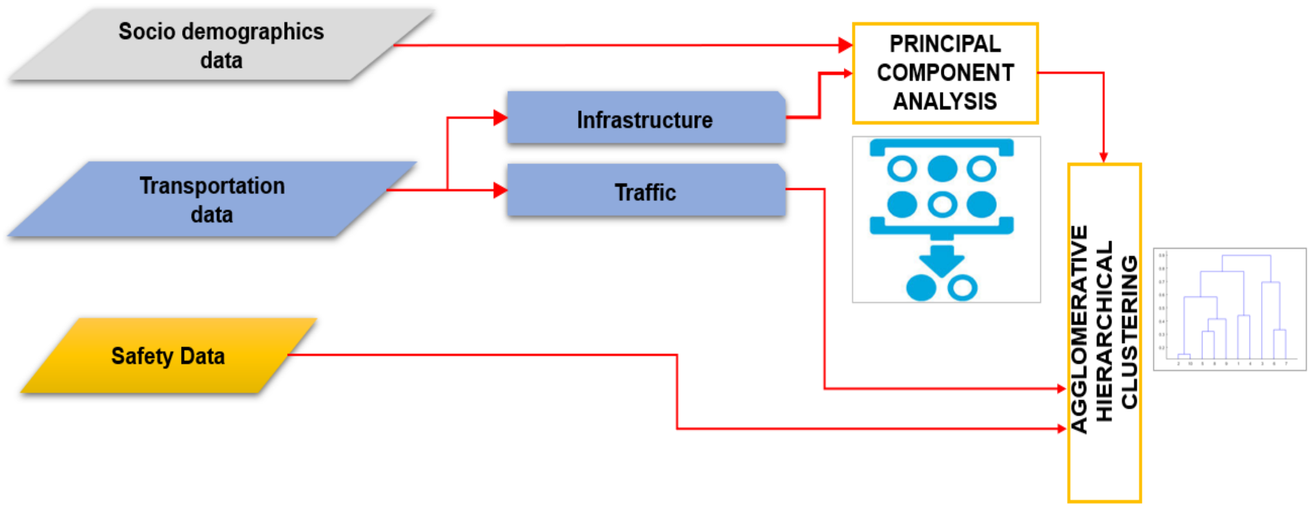


Figure 43 Clustering analysis framework

Development of Scenarios

The dendrogram illustration of the clustering analysis of Texas counties revealed the spatial similarity across the San Antonio region, Dallas Fort Worth, and the city of Austin with respect to the traffic, transportation infrastructure, safety, and socio-demographic and economic attributes (see Figure 44). This facilitated in transferability of existing results. In addition, a research that discusses about the market penetration of different levels has been referred in creating the scenarios for the current study (*206*). It is worth noting that the existing literature indicated two kinds of AV penetrations in the market. Few studies identified that penetration rates would be gradual through different levels (*206*). In contrast, Bansal and Kockelman (*246*) through their analysis identified that the penetration of level 4 AVs would be higher than the Level 3 AVs. Overall, 15 scenarios were developed to include both categories. For the first category, level 4 is not expected to achieve peak rate unless level 3 has achieved a substantial penetration rate. Further, these scenarios are categorized as base conditions (where subsidies in price are not expected) and progressive conditions (where subsidies are expected) as observed in Table 32 and Table 33. Further as suggested by Bansal and Kockelman (*246*), an additional group of scenarios was created where level 4 AVs are preferred over level 3 AVs. Table 34 summarizes different scenarios for this category.

Table 32 AV scenarios under base conditions (category I)

	Scenarios	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Base scenarios	No Automation	65%	35%	25%	10%	5%	0%
	Level 1	20%	45%	30%	20%	15%	10%
	Level 2	15%	20%	40%	55%	45%	35%
	Level 3	0%	0%	5%	15%	30%	50%
	Level 4	0%	0%	0%	0%	0%	5%
	Level 5	0%	0%	0%	0%	0%	0%

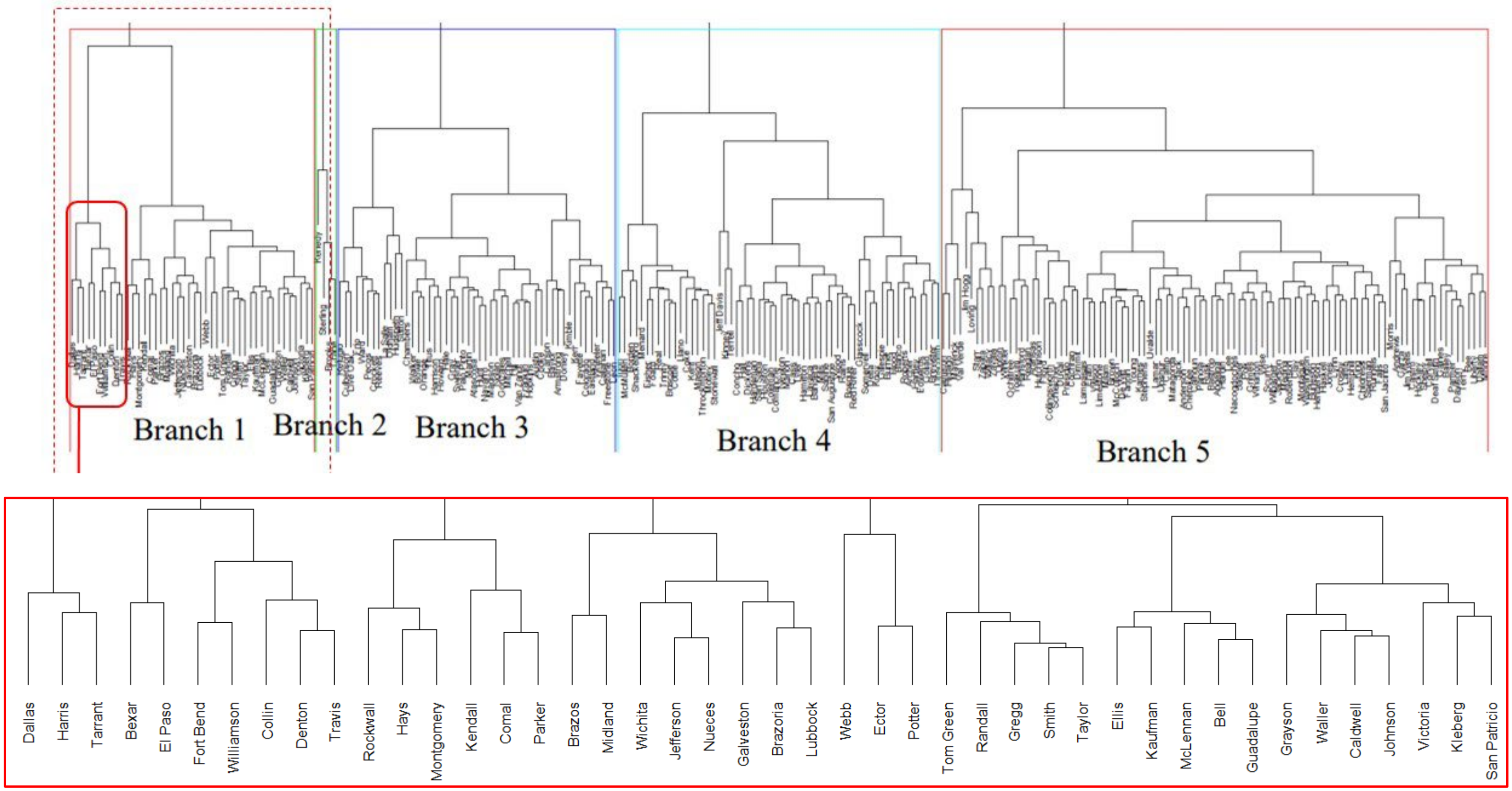
Table 33 AV scenarios under progressive conditions (category I)

	Scenarios	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12
Progressive scenarios	No Automation	40%	25%	5%	0%	0%	0%
	Level 1	20%	15%	10%	5%	0%	0%
	Level 2	25%	30%	25%	15%	5%	0%
	Level 3	15%	25%	45%	55%	35%	25%
	Level 4	0%	5%	15%	20%	45%	55%
	Level 5	0%	0%	0%	5%	15%	20%

Table 34 AV scenarios when level 4 is preferred over level 3 (category II)

Scenarios	Scenario 13	Scenario 14	Scenario 15
No Automation	0%	0%	0%
Level 1	40%	20%	5%
Level 2	32%	45%	55%
Level 3	8%	10%	7%
Level 4	20%	25%	33%
Level 5	0%	0%	0%

Since testing each scenario requires considerable computational effort, it might not be viable to test each scenario and develop recommendations. Hence it is envisioned to test such scenarios which necessitate utmost importance.



Branch 1 members

Figure 44 Tree Dendrogram generated from the cluster output (*247*)

CHAPTER 5: SIMULATION MODELING

Introduction

In an ideal case, AVs will have 100% market penetration. However, a mixed traffic situation where vehicles having different levels of automation are anticipated to interact with manually driven vehicles (*249*) in the near future. The literature suggests that the improvement of the traffic flow will depend on the market penetration of AVs. Automation in driving is anticipated to impact traffic operations, but the magnitude of their effects is still unknown. This chapter used scenarios created from earlier tasks in the project before visiting and examining a number of existing traffic models (car-following models, lane change models), calibrating the parameters for the model that best represented the study region using a microsimulation tool, SUMO (*250*). Calibrated models were then implemented for both interrupted and uninterrupted facilities, therefore developing macroscopic fundamental diagrams along with traffic performance measures to evaluate the efficiency of segments.

Development of Model Parameters for SAE Levels

Car Following Models

Krauss Model: The default car following model provided by SUMO, Krauss Model, is applied for the human-driven or Level 0 vehicles. Krauss Model is the modified version of the model developed by Stefan Krauß in Microscopic Modeling of Traffic Flow: Investigation of Collision Free Vehicle Dynamics (*251*). According to this model, the vehicles are allowed to drive as fast as possible provided the safety criteria are maintained. That is, the follower vehicle is always able to avoid a collision if the leader vehicle starts breaking within the maximum acceleration bounds of the leader and follower vehicle (*250*, *252*). The safe speed is computed as:

$$v_{safe} = v_l(t) + \frac{g(t) - v_l(t)t_r}{\frac{v_l(t) + v_f(t)}{2b} + t_r}$$

Where,

v_{safe} = safe speed,
$v_l(t)$ = speed of the leading vehicle in time t,
g(t) = gap to the leading vehicle in time t,
t_r = driver's reaction time (about 1 sec),
b = maximum deceleration of the vehicle (in m/s^2),
$v_f(t)$ = speed of the following vehicle in time t

As v_{safe} may be larger than the speed limit allowed on the road or the speed capability of vehicles, the minimum of these values is considered as the desired speed (*253*).

$$v_{des} = \min [v_{max}, v + at, v_{safe}]$$

where,

t = step duration of the simulation

ACC Model: ACC is one of the benchmarks for ADAS, which helps to automate the follower vehicle by controlling the throttle and brake of the ACC-equipped vehicle. ACC system contains radar, lidar, and camera, to measure the distance and relative velocity between the follower ACC vehicle and the preceding vehicle. In this study, Level 1 and Level 2 vehicles are equipped with the ACC car following model.

The selected ACC car following model is based on the works of (Liu et al. (*254*), Milanes et al. (*255*), Xiao et al. (*256*)), whereby it is divided into three driving modes. In addition, another driving mode termed collision avoidance mode developed by Transition Areas for Infrastructure-Assisted Driving (TransAID) (*257*) is also discussed below:

1. Speed (or cruising) control mode: The speed control mode of ACC driving is activated when no preceding vehicles are detected in a spacing larger than 120 m. As per this mode, a pre-defined gap by the driver's desired speed is maintained. This mode targets to eliminate the deviation between the desired speed and the vehicular speed which is given by:

   $$a_{i,\,k+1} = k_1\,(v_d - v_{i,\,k}),\; k_1 > 0$$

   where,
   $a_{i,\,k+1}$ = acceleration recommended by the speed control mode of the i^{th} consecutive vehicle for next time step (k+1)
   v_d = desired cruising speed
   $v_{i,\,k}$ = speed of the i^{th} vehicle at the current time step
   k_1 = control gain determining the rate of speed deviation for acceleration = 0.4

2. Gap control mode: This mode aims to maintain a constant time gap between ACC equipped vehicle and its predecessor. It gets activated when the gap and speed deviations are simultaneously smaller than 0.2 m and 0.1 m/sec, respectively. In this mode the deceleration in the next time step (k+1) is modeled as:

   $$a_{i,\,k+1} = k_2 e_{i,\,k} + k_3\,(v_{i-1,\,k} - v_{i,\,k}),\; k_2, k_3 > 0$$

   where,
   $e_{i,\,k}$ = gap deviation of the i^{th} consecutive vehicle
   $v_{i-1,\,k}$ = current speed of the preceding vehicle
   i-1 denotes the leader of vehicle i
   k_2 and k_3 = position and speed deviations control gains, respectively = 0.23 and 0.07

3. Gap-closing control mode: The gap-closing control mode of ACC model was tuned and derived from the gap-controlled mode of CACC model (discussed later). This mode provides a smooth transition between speed control mode and gap control mode. It gets triggered when the spacing to the preceding vehicle is less than 100 m. In situations when the spacing is between 100 m and 120 m, the ACC-equipped vehicle retains the previous control strategy (either speed or gap-closing control mode) to allow a smooth transfer between the speed and gap control mode.
   The values of control gains (k_2 and k_3) are set as k_2 = 0.04 and k_3 = 0.8.
4. Collision avoidance mode: This control mode was developed by TransAID by tuning and modifying the default gap-controlled parameters of the ACC model. This mode prevents rear-end collisions during the simulations. This may occur due to either low time-to-collision value or a follower's speed being significantly higher than that of its leader. The modified values developed by TransAID are, k_2 = 0.8 and k_3 = 0.23.

CACC Model: CACC enables longitudinal AV control with the aid of a combination of sensors and vehicle-to-vehicle (V2V) communication. This allows the follower vehicle to adjust its speed as per the preceding vehicle in its lane (*258*, *259*). The idea of the CACC driving mode is to have a shorter vehicle following gap which in turn improves the traffic performance and allows vehicles to cooperate (*260*). In this study, Level 3 and Level 4 vehicles are equipped with CACC car following model.

Similar to the ACC car following model, the selected CACC car following model is based on the works of (Liu et al. (*254*), Milanes et al. (*255*), Xiao et al. (*256*)). One additional mode, collision avoidance mode developed by TransAID (*257*) is also discussed below:

1. Speed (or cruising) control mode: The speed control mode of CACC driving is similar to that of ACC driving. It is triggered when the time gap is larger than 2 sec. Hence, the control gain is given by:
   $$a_{i,\,k+1} = k_1 (v_d - v_{i,\,k}),\ k_1 > 0$$
   where,
   k_4 = control gain determining the rate of speed deviation for acceleration = 0.4

2. Gap control mode: This mode aims to maintain a constant time gap between CACC equipped vehicle and its predecessor. It gets activated when the gap and speed deviations are simultaneously smaller than 0.2 m and 0.1 m/sec, respectively. In this mode the speed in the next time step (k+1) is modeled as:
   $$v_{i,\,k+1} = v_{i,\,k} + k_5 e_{i,\,k} + k_6 \dot{e}_{i,\,k},\ k_5,\ k_6 > 0$$
   where,
   k_5 and k_6 = position and speed deviations control gains, respectively = 0.45 and 0.0125
   $\dot{e}_{i,\,k}$ = derivative of the gap deviation ($e_{i,\,k}$) = $v_{i-1,\,k} - v_{i,\,k} - t_d \alpha_{i,\,k}$
   where, t_d = desired time gap of CACC vehicle

3. Gap-closing control mode: This mode is activated when the time gap between successive vehicles is less than the minimum threshold of 1.5 sec. The values of control gains for CACC models are k_5 = 0.005 and k_6 = 0.05. In situations when the time gap is between 2 sec and 1.5 sec, the CACC-equipped vehicle retains the previous time step's control strategy.

4. Collision avoidance mode: This control mode was developed by TransAID by tuning and modifying the default gap-controlled parameters of the CACC model. It gets activated in situations when the time gap is below the threshold of 1.5 sec and the gap deviation is negative. The optimal control gain values developed by TransAID are, k_5 = 0.45 and k_6 = 0.05.

Calibration of Lane Change Model

As discussed earlier, current study uses SUMO simulation software in analyzing the capacity of corridors. The default lane changing model in the latest version of SUMO is LC2013. However, this model has been developed for HDVs. Therefore, there is a need to calibrate the model that can replicate the characteristics of SAE levels of autonomy. A similar kind of analysis has been performed in European conditions (*257*). Current study utilized the insights from the above study and extended it for the US environment. As observed in SUMO documentation (*250*) change of lanes of an ego vehicle (vehicle under consideration) is captured in the simulation through several attributes that have different ranges. Sumo developers provided default values for attributes that are applicable for HDVs. In general, the tendency for a vehicle to change its lanes is greatly influenced by the speed of the ego vehicle and speed of surrounding vehicles. Another characteristic that affects the lane change is the gap that the ego vehicle maintains with surrounding vehicles. Therefore, as explained in the report (*257*) primary step was to determine those attributes that predominantly impact the lane changing behavior of a vehicle. The attributes that are present for lane change model LC2013 are described in Table 35 along with their definitions and ranges as obtained from SUMO documentation (*250*).

Table 35 Lane change model (LC2013) attributes along with definitions and ranges

Attribute	Definition	Default Value	Range
lcStrategic	Eagerness to change lanes	1	0 to infinity
lcSpeedGain	Eagerness to change lanes to gain speed	1	0 to infinity
lcKeepRight	Eagerness to stay in the right of a link or edge	1	0 to infinity
lcAssertive	Willingness to accept lower gaps when changing lanes	1	Positive real number
lcCooperative	Willingness to perform cooperative lane change	1	0 to 1
lcLookaheadLeft	Ability to lookahead when a change to left is required	2	0 to infinity
lcSpeedGainRight	Factor used to measure the threshold values when change to left or right is necessary to gain speed	0.1	0 to infinity
lcSpeedGainLookahead	Ability to lookahead expecting a slowdown (seconds)	0	0 to infinity
lcCooperativeSpeed	Adjustment of speeds due to co-operation among vehicle	lcCooperative	0 to 1
lcSigma	Imperfection of vehicle along lateral direction	0	Varies
lcOvertakeRight	Chances to disobey rules by overtaking on right	0	0 to 1
lcOpposite	Willingness to overtake in the opposite direction	1	0 to infinity
lcCooperativeRoundabout	Eagerness to move to inner lanes in a multilane roundabout	lcCooperative	0 to 1

First step of the study was to identify those group of attributes in LC2013 model that shall vary if a vehicle behaves as an autonomous vehicle. For this purpose, a simple freeway segment as shown in Figure 45 has been considered and simulation has been performed with an arbitrary flow of 1800 veh/hr. The considered section is a 2-mile long freeway segment that has an on-ramp and off-ramp. This section is considered owing to its ability to capture maximum number of lane change operations because of weaving. Subsequent step was to identify those group of attributes, that shall vary for AVs. Among the given attributes based on intuition the parameters lcCooperativeRoundabout, lcOpposite, lcOvertakeRight are not expected to differ for AVs. Henceforth, the default values for the specified parameters were considered and was not included in the analysis. After obtaining the group of attributes that are expected to vary, the next step was to perform sensitivity analysis and determine the magnitude of impact each parameter has on the lane change operations of an ego vehicle.

Figure 45 Simple network to calibrate the lane change model

Approach to Sensitivity Analysis

As referred from report (*250*), variance-based sensitivity analysis was considered to be the most appropriate analysis for the current study. The technique formulated by Cukier et.al (*261*) was further modified by Sobol (*257*) and Saltelli et.al (*262*) to improve implementation and efficiency, respectively. This method measures the variance of the considered output variable with respect to the influence of independent variables along with the interactions associated among them. In Sobol analysis (*262*, *263*) variance is measured through two sensitivity indices. First index (S_i) measures the direct effect of independent variables on the dependent variable, it is known as "first-order sensitivity index" and the second index (S_T) measures the effect on output due to interactions between the independent variables. This is known as "higher-order effects." The attributes on which sensitivity analysis has been performed are depicted in Table 36 below. The variance in the dependent variables Leader Gap (distance between ego vehicle on ego lane and leader vehicle in target lane), origLeaderGap (distance between ego vehicle and leader vehicle in ego lane) and follower Gap (distance between the ego vehicle and follower vehicle on target lanes) as demonstrated in Figure 46 were captured through the independent variables as given in Table 36.

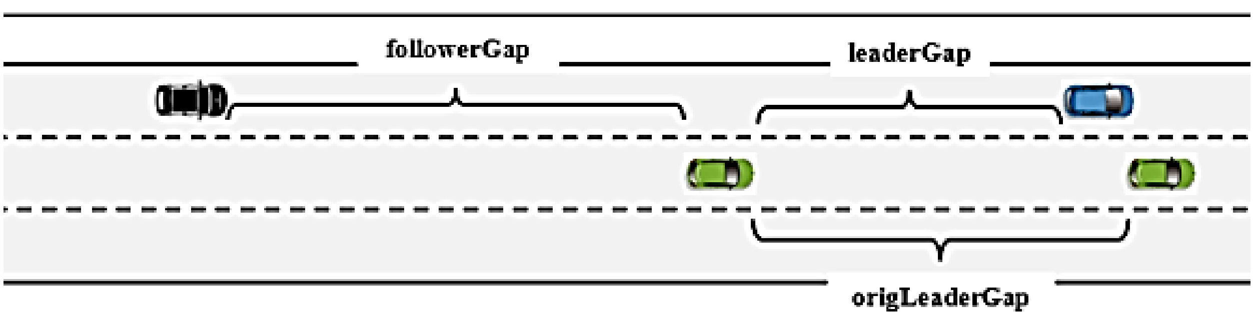


Figure 46 Showing different gaps while changing lanes. Source: Transaid report (*257*)

Table 36 Factors influencing change of lanes

Dependent variables	Independent variables
Leader Gap, Original Leader Gap, and Follower Gap	lcStrategic, lcSpeedGain, lcKeepRight, lcAssertive, lcCoperative, lcLookAheadleft, lcSpeedGainRight, lcSpeedGainLookAhead, and lcCooperativespeed

Sensitivity Analysis Results

The magnitude of sensitivity indices, in general, is a measure of the effect of independent variables on the dependent variable. Ideally, a value of zero shall indicate an insignificant effect of independent variable on dependent variable, however in general a threshold value is often used since complete insignificance cannot be observed often. Therefore, current study has a threshold value of 5 percent and the attributes that had sensitivity indices less than 5 percent were considered inconsequential for further analysis. The sensitivity results are tabularized in Table 37.

Table 37 Sensitivity results for different attributes

S. No	**Attribute**	**Leader Gap (Target lane)**		**Follower Gap (Target lane)**		**Original leader gap (Ego Lane)**	
		S_i	S_T	S_i	S_T	S_i	S_T
1	**lcStrategic**	0.08	0.43	0.04	0.86	0.13	0.41
2	lcSpeedGain	0.05	0.10	0.00	0.17	0.02	0.04
3	lcKeepRight	0.02	0.02	0.01	0.02	0.01	0.01
4	**lcAssertive**	0.28	0.47	0.14	0.41	0.01	0.21
5	lcCooperative	0.00	0.00	0.00	0.00	0.00	0.00
6	**lcLookaheadLeft**	0.31	0.73	0.03	0.45	0.51	0.83
7	lcSpeedGainRight	0.03	0.02	0.03	0.02	0.00	0.01
8	lcSpeedGainLookahead	0.00	0.02	0.04	0.02	0.01	0.01
9	**lcCooperativeSpeed**	0.02	0.12	0.07	0.27	0.12	0.22

Examining the sensitivity analysis results revealed that several variables are insignificantly affecting the gaps. Overall, the attributes that had considerable effect are lcStrategic, lcAssertive, lcLookaheadleft, and lcCooperative Speed. Therefore, it was perceived that only the above-mentioned attributes are expected to vary for AVs. Another characteristic that is important to embrace to replicate the real-world behavior is to incorporate the field observed values for leader gap, original leader gap, and follower gap. The TransAID report (*257*) has utilized values from Hyundai Motor Europe Technical Center (HMETC), so there was a need to validate the transferability of results for US driving conditions. For this purpose, Waymo open source processed data (*264*) has been employed to measure the field gaps. Since the processed data mainly concerned towards understanding the following gaps of AVs, data such as Leader Gap (target lane) and follower gap (target lane) were not able to be extracted. However, the processed data provided great extent of understanding the following behavior of AVs and the gap AV possesses while following a leading vehicle. The following distance of AV with leading vehicle on ego lane was close to 131 ft (40 m) to 148ft (45m) for vehicles traveling at speeds greater than 45 mph. These values were almost similar to that has been observed in TransAID documentation (*257*). Therefore, after examining available field values and existing literature, an assumption has been made that leader gap (target lane), follower gap (target lane) in the US is similar to European conditions. Hence a generalized range of values irrespective of relative speeds was developed as given in Table 38.

Table 38 Utilized gap values for the study

S. No	Variable	Values (in ft)
1	Leader gap	80 - 115
2	Original Leader gap	130 - 150
3	Follower gap	80 - 230

With the value of gaps obtained and knowing the group of attributes that needs to be modified to replicate the above specified gaps, consequent step was to determine the values for these attributes. The attributes were modified by changing one attribute at a time and simulations were run for individual group of parameters. Results of lane change outputs were compared with values as given in Table 38. After running multiple simulations, the outputs were compared and the value for the calibrated parameters was selected as shown in Table 39.

Table 39 Calibrated Lane change model parameters

S. No	Attribute	Value
1	lcStrategic	1.45
2	lcAssertive	1.44
3	lcLookaheadleft	2.15
4	lcCooperative speed	0.71

Parameters for Various Levels

Above sections endeavored on replicating complete autonomous vehicle maneuvers, that include car following and lane changing behaviors. However, in the current research focus lies on comprehending the mixed traffic environment comprising different SAE levels of AVs and HDVs. Therefore, based on the earlier analysis the next effort was to parameterize for different SAE levels. For HDVs, the default car following model (Krauss) and lane changing model (LC2013) has been adopted. Further, longitudinal, and lateral abilities of different SAE levels have been well documented in TM2. Therefore, based on the known capabilities of SAE levels the parameters have been formulated as shown in Table 40.

Table 40 Calibrated model parameters for various SAE levels

SAE level	Car Following model	Lane Change model	LcSigma	Speed Factor		Tau
				Urban	Freeways	
Human driven	Default	LC 2013	Default (=0.5)	Varies	Varies	1
Level 1	ACC	LC 2013	Default (=0.5)	Normc (1,0.1,0.2,2)	Normc (1,0.1,0.2,2)	0.9
Level 2	ACC	LC 2013	0	Normc (1,0.1,0.2,2)	Normc (1,0.1,0.2,2)	0.9
Level 3	CACC	LC 2013 Calibrated	0	Normc (1,0.05,0.2,2)	Normc (1,0.05,0.2,2)	0.7
Level 4	CACC	LC 2013 Calibrated	0	Normc (1,0.0)	Normc (1,0)	0.6

The parameters LcSigma and Tau indicate the lateral movement of a vehicle within the lane and preferred time headways respectively (*250*). Since HDVs and Level 1 has no lateral control, the default parameters have been assumed. Whereas level 2 and above vehicles possess lateral assist systems such as lane centering, these vehicles are expected to move in the center of the lane therefore lateral weaving is assumed to be zero. Further, the minimum time headways are expected to decrease as the level of automation increases therefore based on the car following model the vehicle parameter "tau" has been established. Here, "tau" represents the desirable minimum time headway. Similarly, speed factors for different levels have been developed based on the tendency to align with the posted speed limits. Here, it is important to mention that in this study the assumed parameters are on conservative side as AVs are likely to operate conservatively in mixed traffic condition to avoid incidents. Full potential of AV operation will be realized when their market share is close to 100 percent that can be simulated with more aggressive values of parameters.

Base Model Development

Calibration of the Base Model

Before running a simulation and comparing the traffic performance indices, the base scenario must be calibrated to represent the real-world conditions. In this study, the trial-and-error heuristics method is used to vary the "speedFactor" parameter that is provided as an input to SUMO and the average travel time (for freeways), and the average speed (for urban roads) are compared with the real-world data. The speed factor is an individual vehicle multiplier that gets applied to the speed limit assigned to a particular road. Hence, if the speed factor parameter of a vehicle is larger than 1, it can exceed the speed limit of the road. Speed factor can be defined as a normal distribution with mean, standard deviation, lower bound, and upper bound, that is, speedFactor="normal(mean, sd, lowercutoff, uppercutoff)."

The model is calibrated using Mean Absolute Percent Error (MAPE) which is calculated as:

$$M = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{A_t - F_t}{A_t} \right|$$

Where,

M = MAPE

n = number of times the summation iteration happens

A_t = real field value (travel time or speed)

F_t = value obtained from simulation

Number of Replications

In general, simulation outcomes are stochastic. Therefore, to ensure that the simulation results are statistically significant, we need to determine the number of simulations runs. The coefficient of variation (COV) is used as a measure for establishing the number of simulations required per scenario (*265*). The COV is the ratio of standard deviation to mean. In this study, the COV is calculated for five and ten runs and the run with the least variation is selected. The average speed of the network is used as the measurement criteria.

- COV for five runs = 0.004806 = 0.480577%
- COV for ten runs = 0.00479 = 0.479009%

Hence, ten replications per scenario are considered in this study.

Freeway Section

The calibrated model parameters presented in Table 6 were simulated in both uninterrupted facilities and interrupted facilities. This section discusses the freeway corridor that was implemented in this study and the subsequent section deals with model findings related to two urban corridors. Two categories of analysis were performed for selected freeway corridor in the current analysis.

In the first category, the simulation was executed for a paradigm where all SAE levels use only HOV lanes. The rationale behind such an approach is to test for the performance of AVs when dedicated or "nearly dedicated "lanes are provided. Such analysis would dictate the optimal level of market penetration till which this type of approach is valid. Since having an additional lane for AVs throughout infrastructure is unrealistic and is a substance of huge economic investment, allowing the AVs to use only HOV lane was considered as a suitable available alternative. This would not only lead to efficient usage of available infrastructure but also provides an opportunity to benefit from the cost savings. In addition, at a time where AV technology is still growing reducing the number of interactions of AVs along with HDVs can substantially improve the confidence of vehicle manufacturers to test the vehicles on public roads during the initial stages of market penetration. Therefore, considering the plausible benefits that can arise when AVs share the HOV lane, this particular analysis was considered.

In the second category, a more generalized approach has been taken for testing the performance of AVs. In this corridor AVs are imposed to share the roads along with HDVs, such consideration is critical since AVs are required to share the space and traverse seamlessly with the existing traffic. Hence, for this purpose in this analysis in the considered I-10 corridor, AVs are allowed to use any lane including the HOV lane. The goal of this analysis is to realize the magnitude of capacity improvement when AVs start to exist on roads. Further details on the method of implementation have been elaborated in subsequent sections. Traffic performance for freeways has been measured through the development of Macroscopic Flow Diagrams (MFD). MFDs have been developed by determining the average volume per lane (veh/hr/ln) against average density (veh/mile/ln). The volumes and density are weighted with the length of edge as shown below:

$$average\ volume\ per\ hr\ per\ lane = \frac{\sum_{i=1}^{n} \frac{vol_i * l_i}{n_i}}{L}$$

$$density = \frac{\sum_{i=1}^{n} density_i * l_i}{L}$$

Where;

vol_i	-	volume measured on i^{th} edge
l_i	-	length of edge (lane) *i* along considered route
n_i	-	number of lanes on the edge *i*
L	-	route length (sum of the length of all edges along the given route)
$density_i$	-	density along edge *i*

Analysis for Category 1: HOV Segment (Near Dedicated)

Study Area Characteristics and Traffic Composition

An HOV lane section along interstate 10 was considered for the primary analysis of the study. The study corridor was approximately 6 mile long extending from La Cantera Parkway to FM 3351 as seen in Figure 47 (*266*). The number of lanes varied from 3 to 5 along the corridor. The study section was imported from OSM maps into SUMO and corrected for any discrepancies. Traffic composition and the input flow for the corridor has been obtained from TxDOT STARS Traffic count database system (*267*). A non-weekend day in December 2020 was chosen to provide the input flow and the peak hour flow was observed at 4 pm as represented in Table 41.

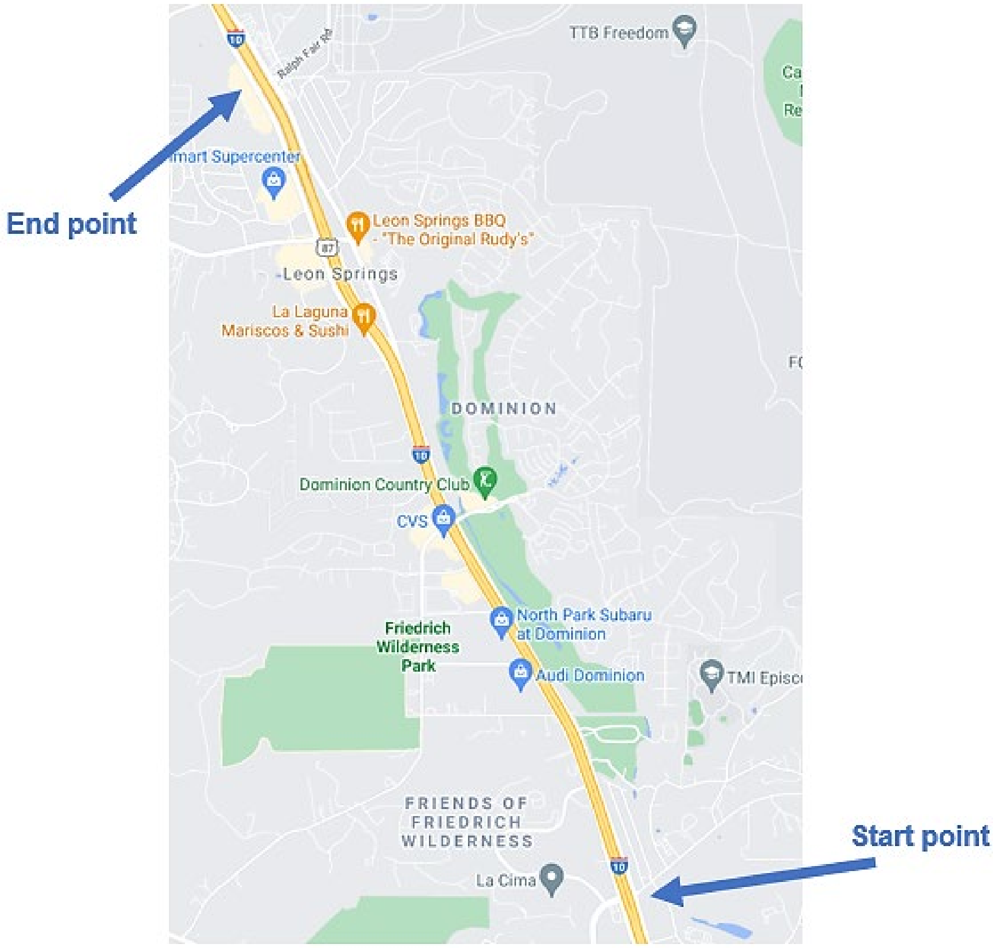


Figure 47 Study segment for freeway capacity analysis (I-10 corridor)

Table 41 Peak hour traffic composition for I -10 corridor

Start Time	8:00 AM	4:00 PM
Car	1795	2609
Pickup	983	1121
2A SU	1	14
BUS	137	46
3A SU	34	13
>3A SU	3	2
<5A 2U	11	8
5A 2U	111	121
>5A 2U	3	4
<6A >2U	7	0
6A >2U	2	1
>6A >2U	0	0

14	0	0
15	0	0
Total	3087	**3939**

Calibration of the Base Model

Travel time was considered as the calibration parameter to reproduce the real-world conditions. The model is to be calibrated till the simulated values lie within the threshold of ± 5 % of field observed travel time. Field observed travel time was obtained from Streetlight data (*268*). The model was adjusted for speed distribution until MAPE was below 5 percent and suitable speed distribution was used for the analysis. In this case, the default speed distribution proved to perform well as given in Table 42.

Table 42 MAPE Comparison between various Speed factors

S. No	Speed Factor	Speed Distribution	MAPE
1	Default	Normc (1,0.1.0.2,2)	0.0435
2	Trial 1	Normc (0.9,0.1.0.2,2)	0.1264
3	Trial 2	Normc (0.8,0.1.0.2,2)	0.1895
4	Trial 3	Normc (0.7,0.1.0.2,2)	0.2153

Analysis for Category 2: I-10 Segment with No Dedicated Lane

The HOV corridor that has been used in the first analysis has been considered for the second analysis too, with the exception being that the AVs can use any lane as mentioned earlier. The calibrated base model in the earlier analysis was utilized for this segment as well.

Urban Section

Two urban corridors are simulated in SUMO to understand the effects of automation on traffic performance measures. The study is done by providing static routing and turning probabilities at specified intersections. Ten simulation runs per scenario are considered and the average values of those ten runs are taken as the output. Tests are conducted for the peak hour flow of a particular day and by doubling the peak hour flow at an interval of 25%. The latter is done to understand the capabilities of the current infrastructure to withstand the foreseeable future demands.

In the first corridor, the simulation was performed assuming that SAE Level 3 vehicles can navigate through a traffic light-controlled (TLC) intersection on their own. SAE level 3 is conditional automation whereby the automation features work only on certain conditions and is also limited by the ODD. This assumption may increase the traffic performance of level 3 vehicles as the disengagement and transition of control to human drivers would substantially reduce the performance of vehicle.

In the second corridor, the disengagement of level 3 vehicles has been incorporated and tested for the changes in traffic performance. It is assumed that Level 3 vehicles cannot navigate “all way” stop on their own and therefore will disengage and switch the control back to the human driver. The implementation methodology has been explained in subsequent sections.

Traffic performance of an urban corridor can be measured through various performance indicators: speed, travel time, queue length, number of stops, waiting time, etc. In this study, the outputs given by the edge-based measurement of SUMO are post-processed to obtain the desired corridor performance: average speed (mph), average travel time (sec), and average waiting time (sec/veh). Each of them is explained below:

- Average speed (mph): The average speed of each edge is obtained as an output from SUMO. The average speed of the corridor is calculated by normalizing the average speed of an edge with the number of vehicles in that edge for the specified time period.

$$v = \frac{\sum_1^n v_i * nv_i}{\sum_1^n nv_i}$$

- Average travel time (sec): The average travel time of each edge is obtained from SUMO which is summed to obtain the average corridor travel time. This value is based on the time needed for the front of the vehicle to pass the edge/link.

$$tt = \sum_1^n tt_i$$

- Average waiting time (sec/veh): The total number of seconds vehicles were considered halting (speed < speed threshold) summed up over all the vehicles present in the edge is obtained from SUMO. The speed threshold is taken as 0.1 m/s. The average waiting time for the corridor is obtained as below:

$$wt = \sum_1^n \frac{wt_i}{nv_i}$$

Where,
v_i = average speed of i^{th} edge
nv_i = number of vehicles in i^{th} edge
tt_i = average travel time in i^{th} edge
wt_i = total waiting time in i^{th} edge summed over all the vehicles passing that edge

Urban Study Corridor 1: East Commerce Street (TLC Intersection)

Study Area Characteristics and Traffic Composition

A 2-mile section of East Commerce Street (E Commerce ST), a four-lane (two lanes per direction), in the downtown of San Antonio, Texas is used as the first test urban corridor for this study as shown in Figure 48. The following assumptions are made for this study region:

- No U-turns allowed,
- Intersections having no traffic lights are discarded,
- Sumo built-in actuated traffic light system (time gap based) having a cycle length of 90 secs is applied,
- No modal split (only passenger cars considered),
- SAE level 3 AVs can navigate TLC intersections on their own.

The study region contained seven arterial roads: E Commerce ST, Cherry ST, Hackberry ST, New Braunfels Ave, Gevers ST, Walters ST, and Mel Waiters Way as shown in Figure 48. Real world turning counts obtained from the Streetlight Data (*268*) are implemented in each of these six intersections and the corridor analysis is done for E Commerce ST (depicted by red color).

The speed limit on each of the abovementioned arterial roads (shown below) is taken from TxDOT's open-data ArcGIS archive (*269*).

- E Commerce ST: 35 mph
- Cherry ST: 30 mph
- Hackberry ST: 30 mph
- New Braufels Ave: 30 mph
- Gevers ST: 30 mph
- Walters ST, NB: 30 mph and SB: 35 mph
- Mel Waiters Way: 30 mph

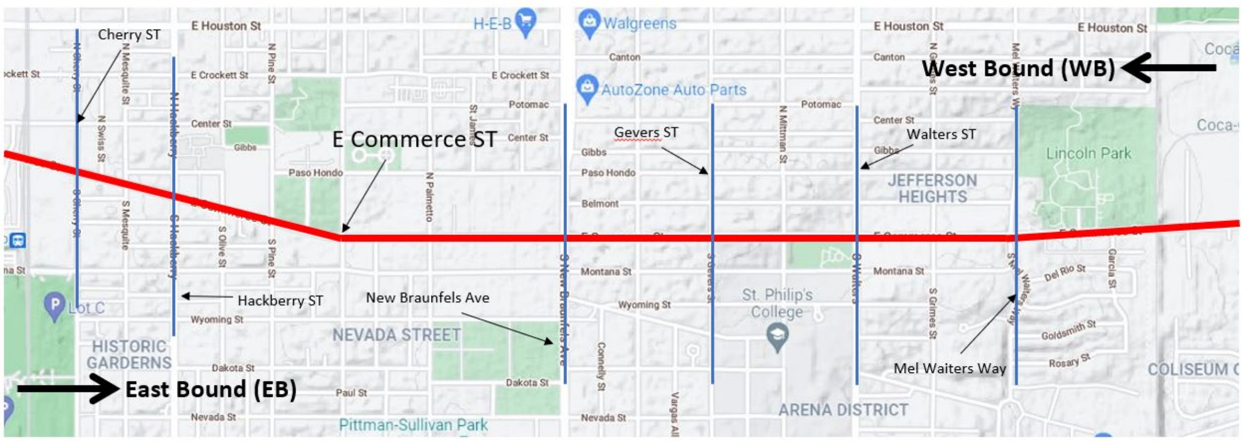


Figure 48 Urban corridor (East Commerce Street)

The input flows (turning count and through movements) are taken from the Streetlight Data for the peak-hour of a typical pre-COVID weekday (09/10/2019). The morning peak hour was from 7 am to 8 am while the evening peak hour was from 7 pm to 8 pm as shown in Table 43. The simulation is conducted for the input flow of the higher peak hour, from 7 pm to 8 pm, with a warm-up period of 1000 seconds. An overview of the intersection count data given by Streetlight is shown in Figure 49. It represents the traffic movement between E Commerce ST and Cherry ST.

Four additional traffic scenarios are also considered whereby the current real-world traffic counts are increased by 25%, 50%, 75%, and 100% respectively to achieve more congestion and explore the trend and effects of various levels of automation under these situations.

Table 43 Streetlight Segment (E Commerce ST) Traffic

Time of Day	Average Traffic (per hour, bi-directional)
6am-7am	291.11
7am-8am	**911.44**
8am-9am	546.06
9am-10am	533.56
10am-11am	442.50

11am-12noon	562.00
12noon -1 pm	728.72
1pm- 2 pm	560.83
2pm-3pm	650.83
3 pm-4pm	697.67
4pm-5pm	962.44
5pm-6pm	848.17
6pm-7pm	895.39
7pm-8pm	**1033.94**
8pm-9pm	787.00
9pm-10pm	229.89

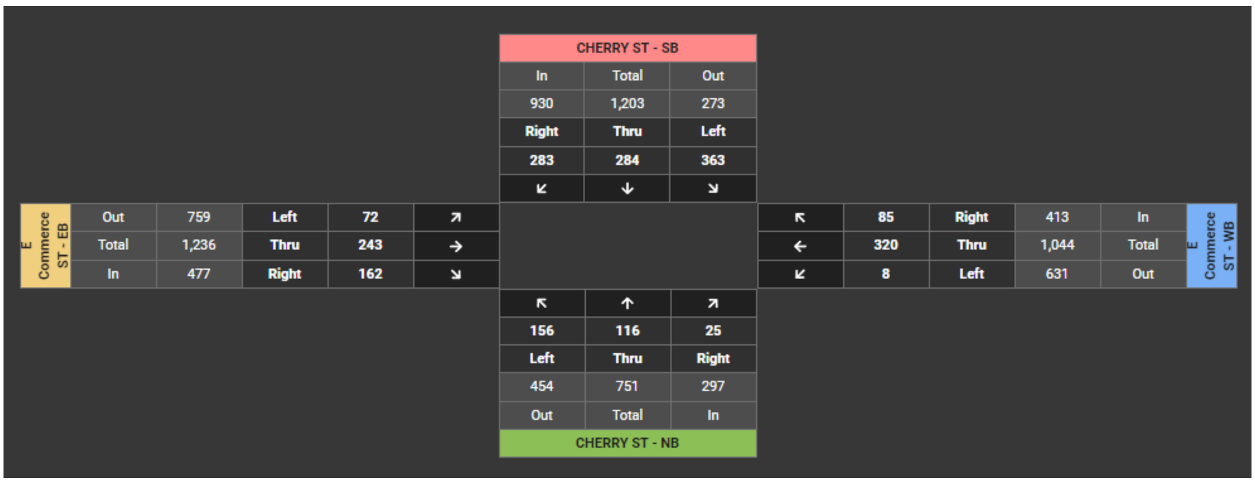


Figure 49 Typical streetlight intersection turning counts data format

Calibration of the Base Model

Using MAPE the percent error in the average speed of the corridor is calculated for four values of "speedFactor" as shown in Table 10. The scenario where MAPE is the minimum is considered as the base case of the corridor. Hence, speedFactor of 0.8 is selected as the base model.

Table 44 MAPE (urban corridor 1)

Model	**MAPE**
Default	0.255335
speedFactor = 0.9	0.144062
speedFactor = 0.8	0.018392
speedFactor = 0.7	0.107581

Urban Study Corridor 2: Babcock Road (All Way Stop Intersection)

Study Area Characteristics and Traffic Composition

A 2-mile stretch of Babcock Road (Babcock RD), a four-lane (two lanes per direction), in Northwest San Antonio, Texas is used as the second test urban corridor for the study as shown in Figure 50. The following assumptions are made for this study region:

- No U-turns allowed,
- Sumo built-in actuated traffic light system (time gap based) having a cycle length of 90 secs is applied,
- No modal split (only passenger cars considered).,
- Level 3 vehicles will disengage and give control to HDVs (switches to Level 2) when all way stop is encountered.

The study corridor contained three intersections: two TLC and one all way stop. The reason for choosing this corridor was to capture the disengagement behavior of Level 3 vehicles. This section has enough space and time for Level 3 vehicles to switch the control back to and from human. Similar to the first urban corridor, Streetlight Data (*268*) is used to obtain the turning movement counts at the three intersections. And the analysis is done for the EB and WB direction of Babcock RD corridor, shown by the red line, in Figure 6. The speed limits are taken from TxDOT's open-data ArcGIS archive (*269*) and implemented on the network development accordingly.

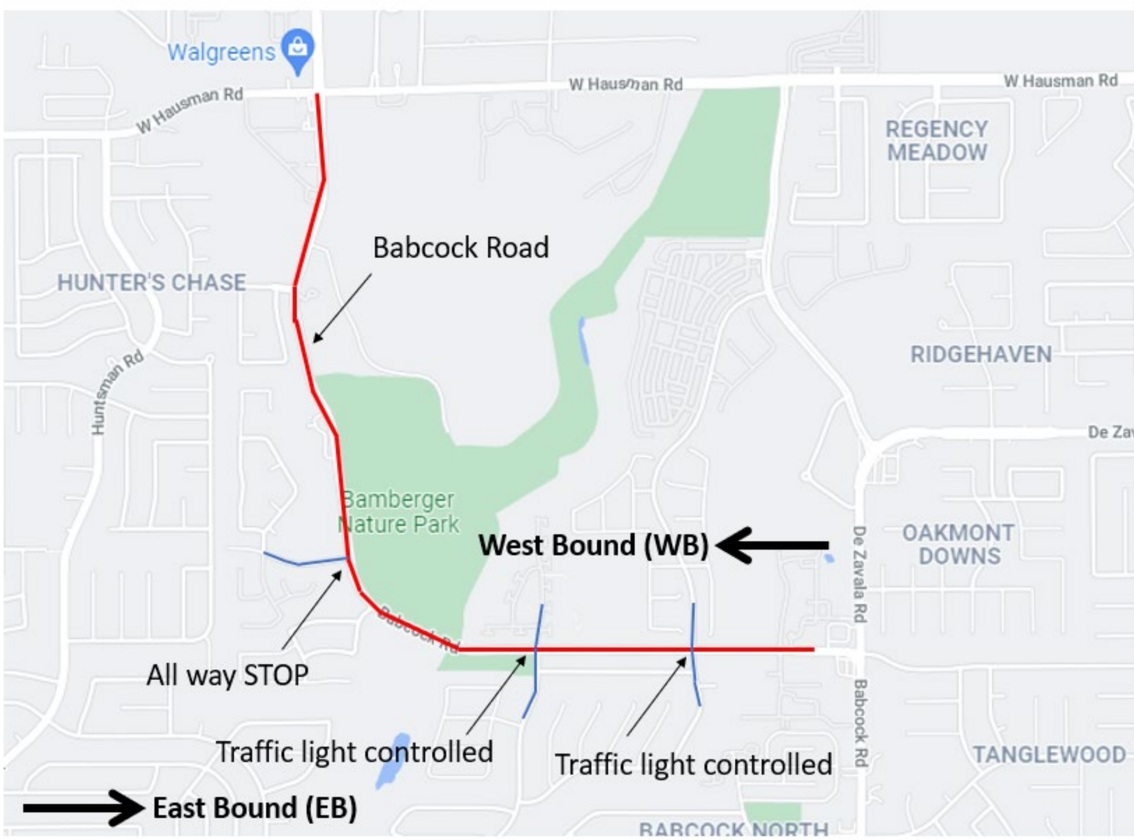


Figure 50 Urban corridor (Babcock Road)

The input flows (turning count and through movements) are provided for the peak hour of a typical pre-COVID weekday (09/10/2019). The morning peak hour was from 7 am to 8 am while the evening peak hour was from 5 pm to 6 pm as shown in Table 45. The simulation is conducted for the input flow of the higher peak hour, from 5 pm to 6 pm, with a warm-up period of 1000 seconds. Similar to the first urban corridor, four additional traffic scenarios are considered whereby the current real-world traffic counts are increased by 25%, 50%, 75%, and 100% respectively to achieve more congestion and explore the trend and effects of various levels of automation under these situations.

Table 45 Streetlight segment (Babcock RD)

Time of Day	Average Traffic (per hour, bi-directional)
6am-7am	366.3125
7am-8am	**1021.125**
8am-9am	604.8125
9am-10am	514.5625
10am-11am	614.1875
11am-12noon	539.75
12noon -1 pm	539.4375
1pm- 2 pm	774.6875
2pm-3pm	644.3125
3 pm-4pm	626.6875
4pm-5pm	1196.125
5pm-6pm	**1610.8125**
6pm-7pm	1112.5
7pm-8pm	895.6875
8pm-9pm	572.3125
9pm-10pm	535.5625

Calibration of the Base Model

The percent error in the average speed is calculated for various values of "speedFactor" as shown in Table 46. The scenario where MAPE is the minimum is considered as the base case of the corridor. Hence, speedFactor of 0.95 is selected as the base model.

Table 46 MAPE (urban corridor 2)

Model	MAPE
Default	0.028353
Speed factor = 0.95	0.026591
Speed factor = 0.9	0.072601
Speed factor = 1.05	0.06189
Speed factor = 1.1	0.105456

Simulation

Scenario Development

To measure the impact of AVs on the capacity of expressways and traffic performance of urban road at various market penetration levels, scenarios that were generated in the earlier phase of the study was implemented. These scenarios are a comprehensive consolidation of different possibilities of AV market penetration in the future. Consolidated list of different scenarios that were utilized in the study is presented in Table 47.

Table 47 Different scenarios used for traffic performance evaluation

Scenarios	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
No Automation	65%	35%	25%	10%	5%	0%
Level 1	20%	45%	30%	20%	15%	10%
Level 2	15%	20%	40%	55%	45%	35%
Level 3	0%	0%	5%	15%	30%	50%
Level 4	0%	0%	0%	0%	0%	5%
Level 5	0%	0%	0%	0%	0%	0%

Scenarios	Scenario 7	Scenario 8	Scenario 9	Scenario 13	Scenario 14	Scenario 15
No Automation	40%	25%	5%	0%	0%	0%
Level 1	20%	15%	10%	40%	20%	5%
Level 2	25%	30%	25%	32%	45%	55%
Level 3	15%	25%	45%	8%	10%	7%
Level 4	0%	5%	15%	20%	25%	33%
Level 5	0%	0%	0%	0%	0%	0%

Among the generated scenarios three scenarios (Scenario10, Scenario11, Scenario12) were excluded in the study. The above three scenarios had a reasonable extent of level 5 AV vehicle penetration and owing to the absence of field data for level 5 AVs to calibrate the models the scenarios having level 5 vehicles were not considered for further analysis. The scenarios presented are originated from an existing study (*270*). Hence the scenarios developed here are scenario 1 to scenario 6 which represents the case where the support for AV industry is not extravagant and hence AV growth is assumed to be normal. On the other hand, the erstwhile developed scenario 7 to scenario 12 represents a case where the support for the adoption of AVs is enormous in the form of providing incentives, subsidies, etc. Therefore, the growth of AVs between these scenarios or the rate of adoption is high. Scenario 13 to scenario 15 form another distinct group where the level 3 AVs are not preferred because of giving control to human drivers. Therefore, the above-described scenarios have three distinct groups Group 1(scenario 1 to scenario 6), Group 2(scenario 7 to scenario 9), and Group 3(scenario 13 to scenario 15). Henceforth, the results of the study are discussed in line with the corresponding groups.

Capacity Analysis on Freeways

Subsequent action in the analysis is to examine the impact on the capacity of the corridor under different considered scenarios. Prior to discussing on the results of analysis, certain assumptions were made to avoid intricacy in the analysis. They are as follows:

- In freeways, autonomy is considered to exist only in the passenger cars therefore all classes of vehicles except passenger cars are contemplated to be human driven only.
- The level 3 and level 4 AV are considered to have low value of co-operation as depicted through Table 5. This is considered based on available field data and existing literature. Henceforth, the assumption is conservative which can impact the traffic flow when a high number of lane changes are involved.

As discussed earlier, the macroscopic fundamental diagrams were developed between volume and density to obtain the capacity of corridors.

Analysis for Category 1: HOV Segment (Near Dedicated)

Field observed flow was provided as base demand initially and later increased to capture the capacity. Simulations were run until the flow values reached to peak value and started dropping substantially. Finally, the plots were made with volume per hour per lane against density per mile.

Capacity Analysis

Examining the fundamental diagrams provides an interesting insight into the manner in which the capacity of HOV lane gets impacted. It is evident that under complete HDVs, the segment considered had capacity close to 1800 veh/hr./ln as shown by Figure 51. With the increase in vehicle automation, the capacity was found to improve to a certain extent, and then it started to decline. This trend has been observed in all three groups.

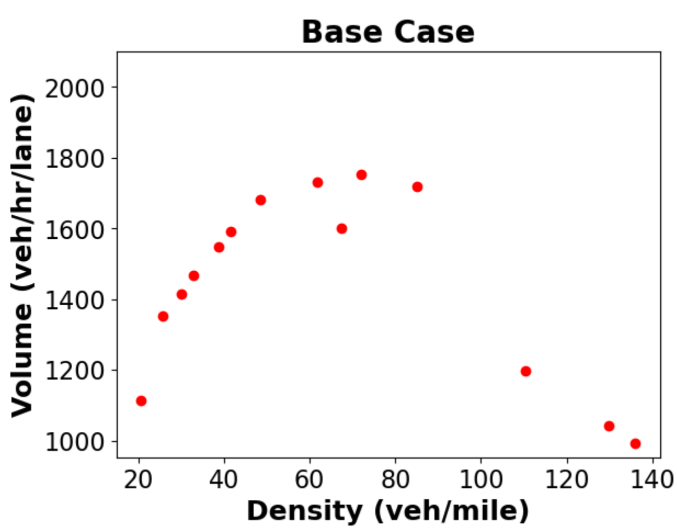


Figure 51 Flow vs Density curve for base scenario

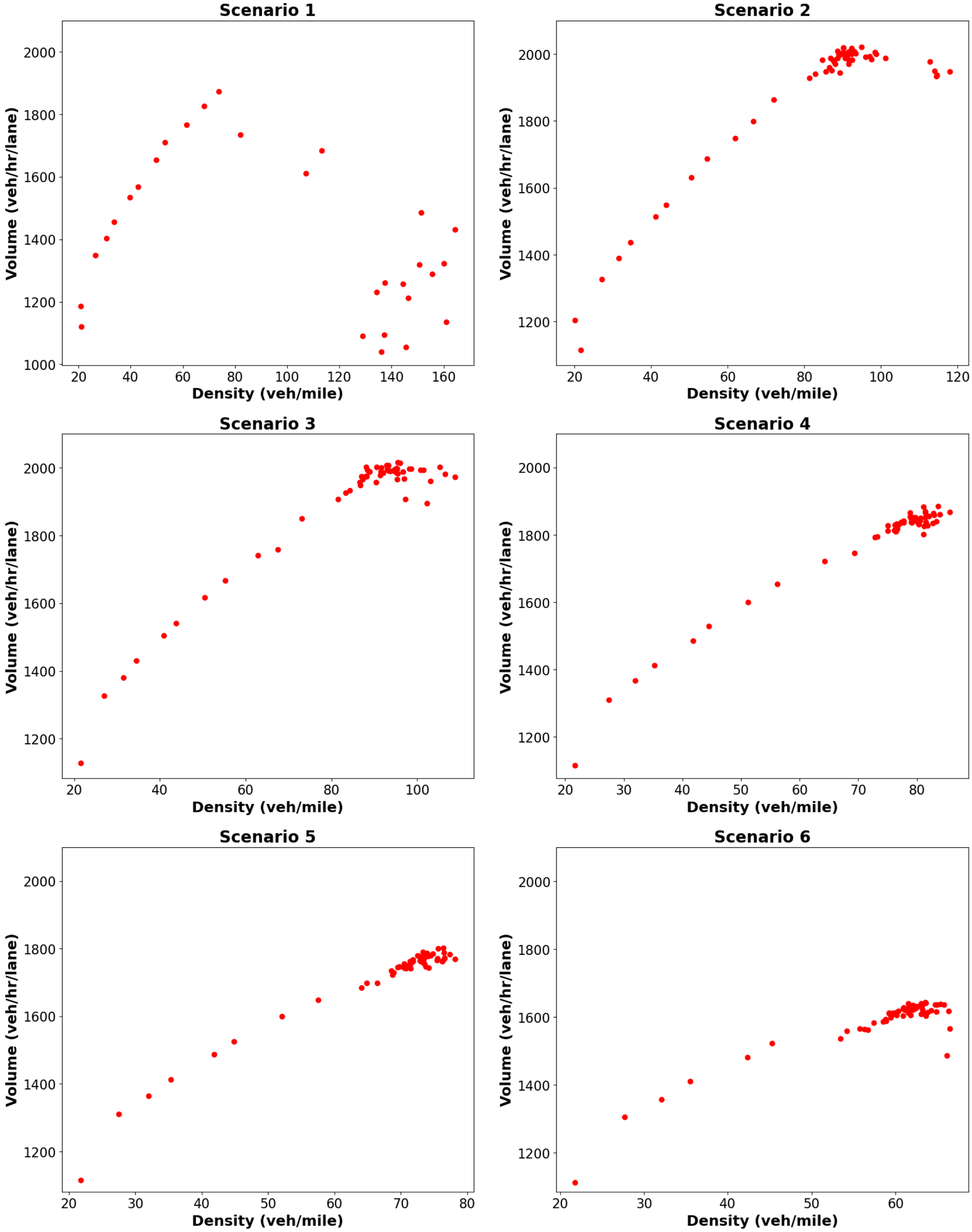


Figure 52 Flow vs Density curve for group 1 scenarios near dedicated situations

In group 1 (Figure 52) the highest capacity was found for scenario 2 and scenario 3, where the capacity reached up to 2000 veh/hr/ln and then it started to diminish from scenario 4 onward till scenario 6. This rate of decline is observed to such an extent that scenario 6 performed worse than HDVs resulting in lower capacity values.

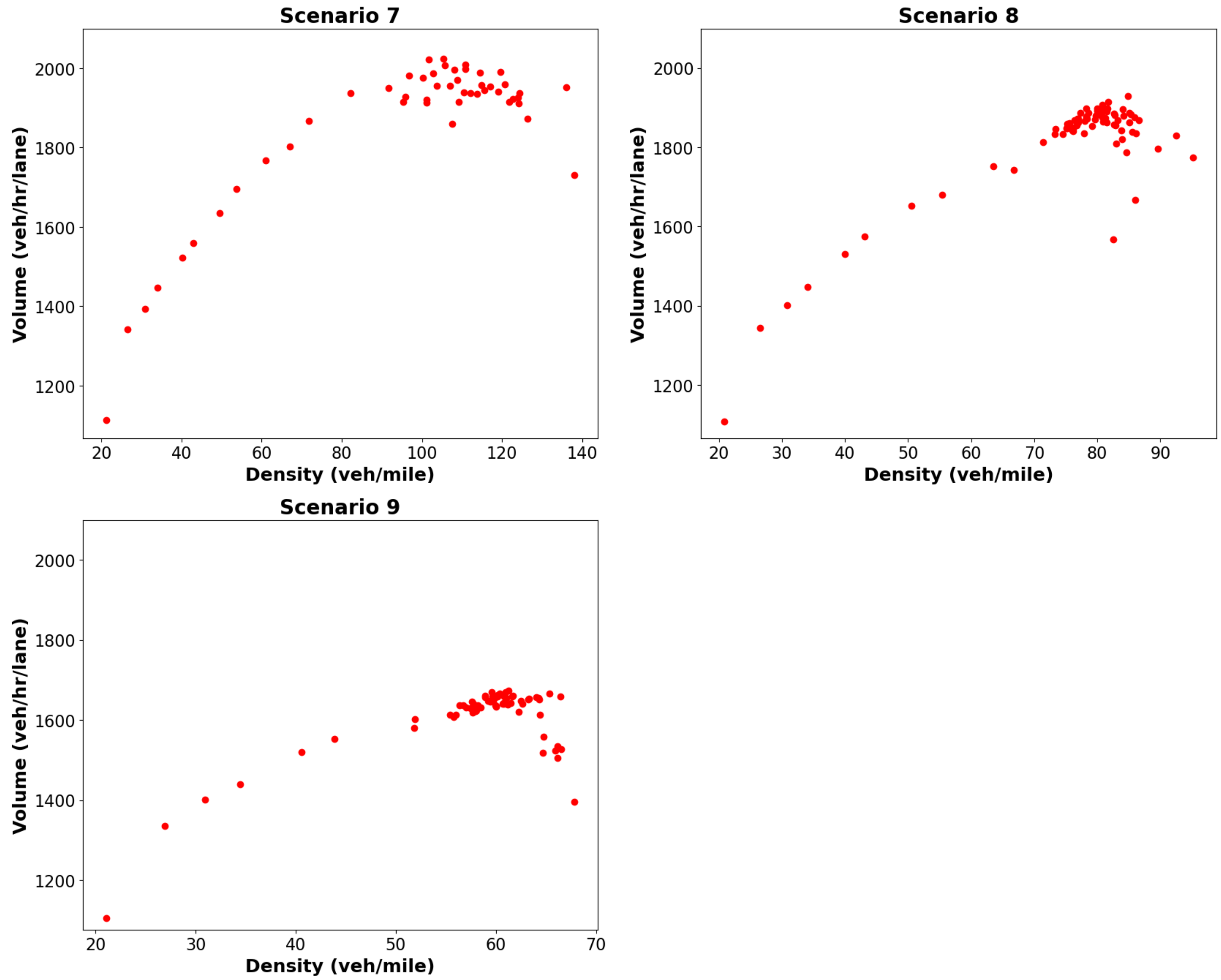


Figure 53 Flow vs Density curve for group 2 scenarios under near dedicated situations

Similarly, when group 2 scenarios were investigated akin inferences could be derived. By farthest scenario 7 and to some extent scenario 8 performed better when compared to base scenarios whereas scenario 9 performed inferior to HDVs as depicted by Figure 53. An appropriate inference that can be made from the above results is that providing a “nearly” dedicated lane such as an HOV lane for AVs is found to improve the traffic performance when partially AVs are predominant. Further at higher market share of AVs although with high automation levels, as expected the capacity drop is observed owing to underutilization of infrastructure. Therefore, it is extremely important to recognize the tradeoff between having a dedicated infrastructure to AV and improvement in traffic performance. Therefore, after a particular penetration level the dedicated lane (where AVs are only allowed in HOV lane) can have a deteriorating impact on performance. However, intuitively separating AV from HDV may have positive impact on the safety outcomes although that needs to be investigated.

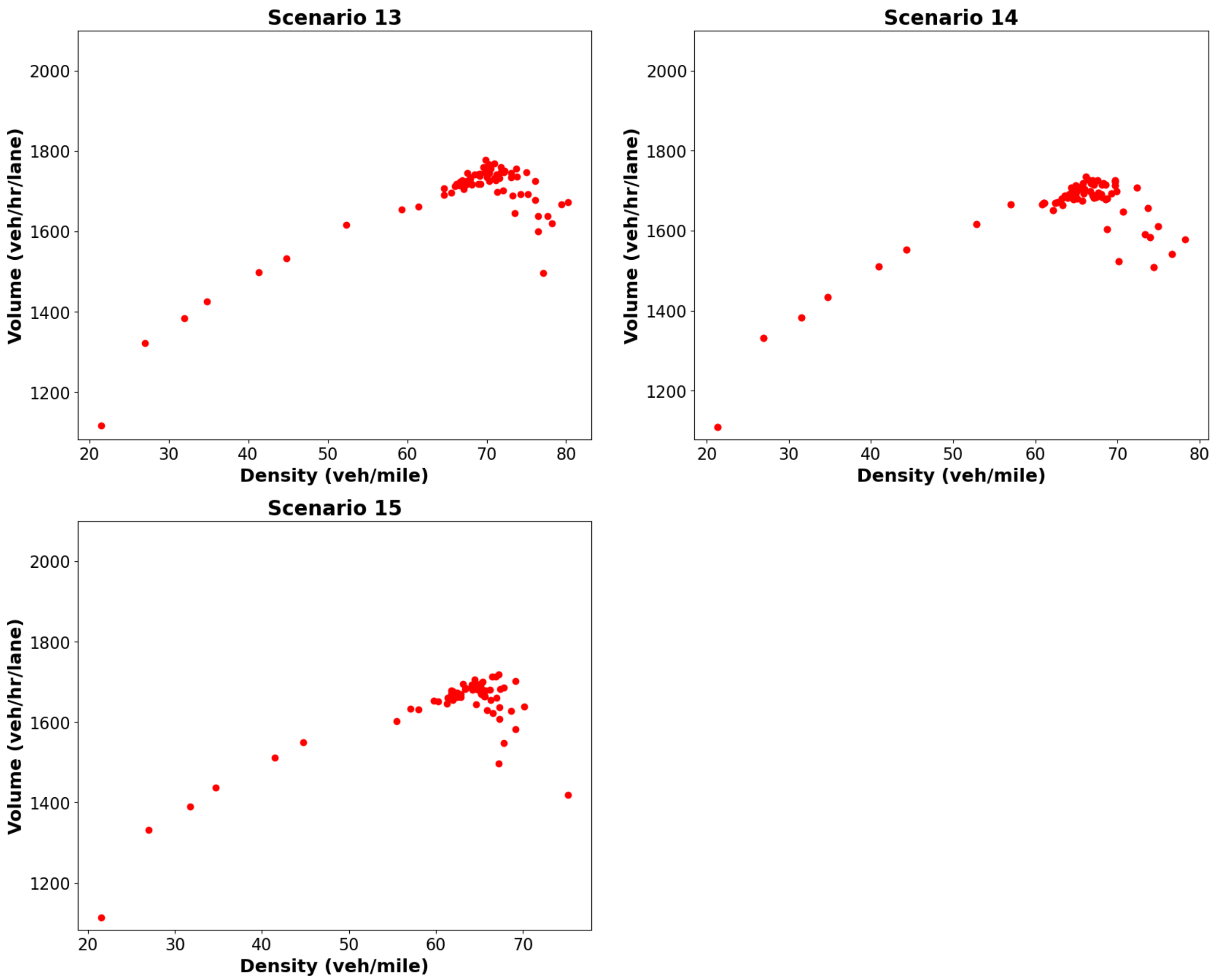


Figure 54 Flow vs Density curve for group 3 scenarios under near dedicated situations

These results are resonated in group 3 scenarios as well. As seen in Figure 54, in the scenarios that had higher penetration of AVs such as scenario 13 through 15, the capacity was equivalent to that of base case. As mentioned earlier the reason being the dedicated lane is considered getting saturated at earlier penetration rates. Overall, it can be concluded that restricting AVs to use dedicated infrastructure is highly beneficial when the penetration levels are low to medium particularly when it is dominated by partial AVs such as up to SAE level 2.

Analysis for Category 2: I-10 segment with NO Dedicated Lane

In this analysis, the aforementioned freeway corridor has been considered, however, in this deployment, AVs are free to utilize any lane and not restricted to use only HOV lane. The base capacity of the segment can be visualized from Figure 51.

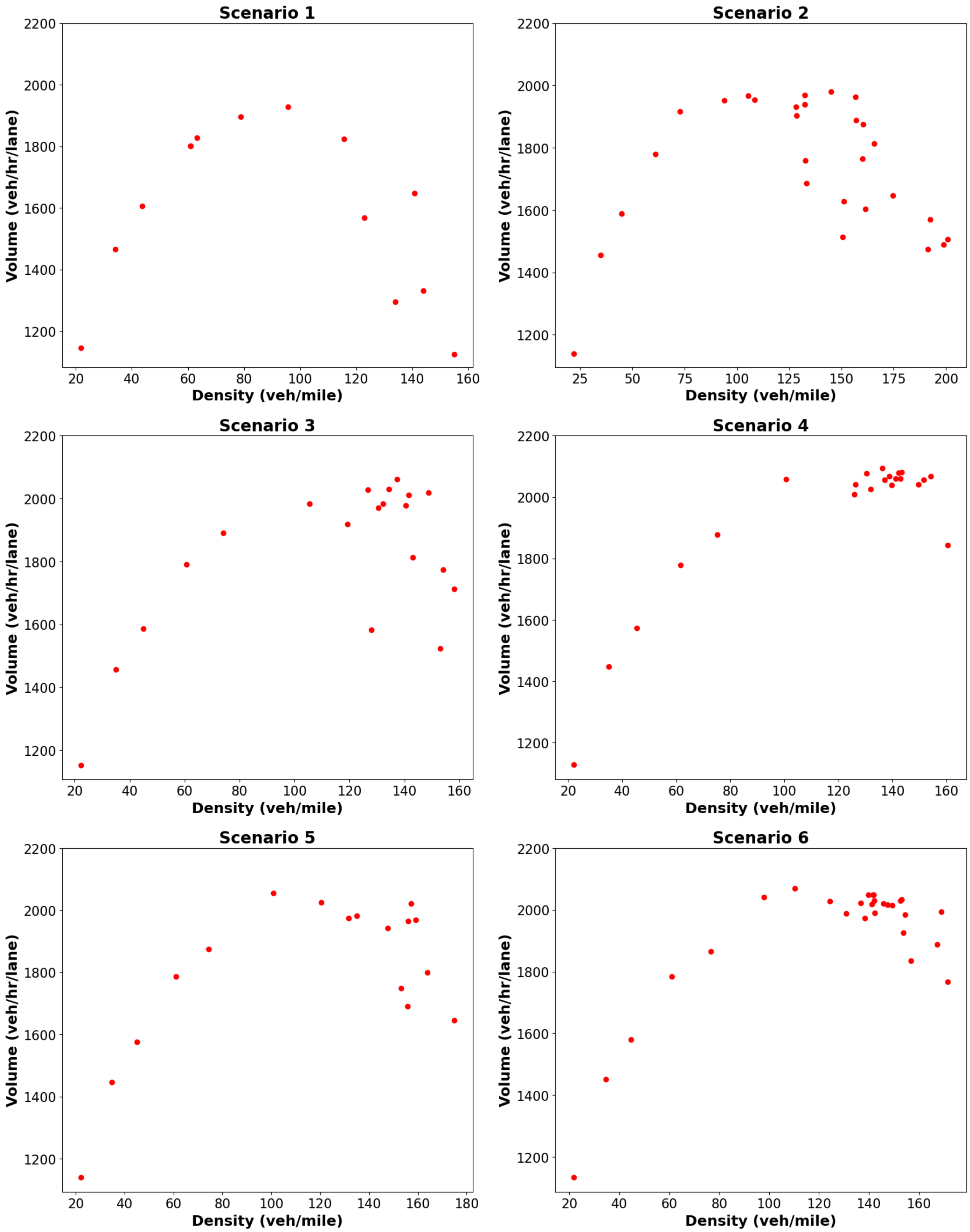


Figure 55 Flow vs Density curve for group 1 scenarios under unrestricted situations

Similar to the trend that has been observed in group 1 of first analysis, the capacity increased with vehicle automation. However, it is interesting to note at lower levels of AV market penetration the results in analysis 1 showed better capacity values. As the market penetration increased scenario 4 through 6, the results in analysis for category 2 showed better results with capacity values reaching up to 2140 veh/hr/lane at scenario 6 where there is a predominant percent of level 2 and level 3 vehicles as highlighted by Figure 55. This increase is a significant difference from what it was observed in dedicated lanes. Therefore, transitioning the AVs or allowing the AVs to use complete infrastructure from scenario 4 i.e., when SAE level 2 vehicles are almost 50 percent of the passenger cars and when level 3 vehicles start to gain prominence, it yields better traffic performance.

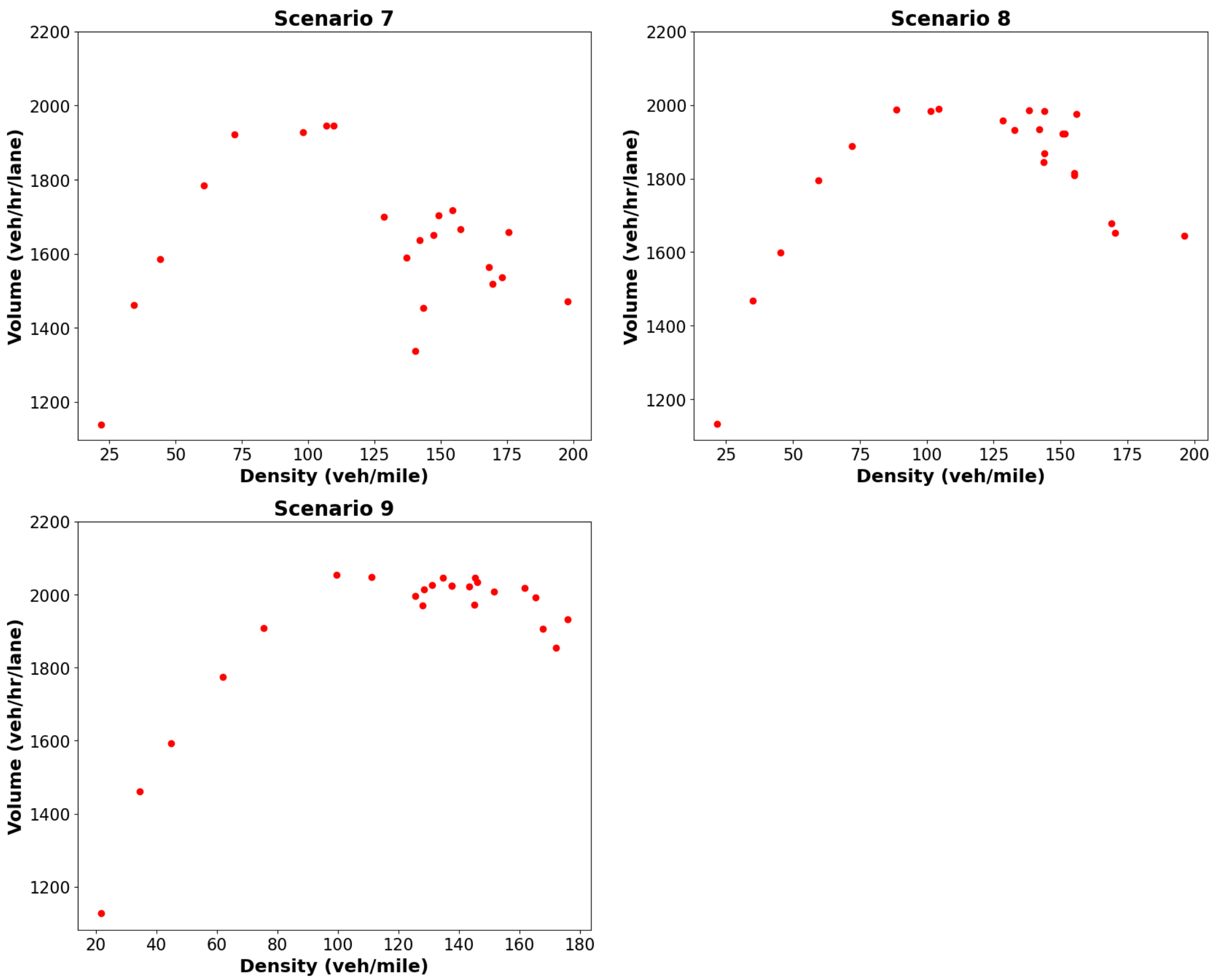


Figure 56 Flow vs Density curve for group 2 scenarios under unrestricted situations

Group 2, as shown by Figure 56, shall also prove a similar case since both group 1 and group 2 scenarios signify alike situations in the future with the only difference being that in group 2 the rate of penetration of SAE levels would be quicker as compared to group 1 scenarios. In group 2, scenario 9 where the level of penetration is almost close to 80 percent, the capacity reaches the peak at 2160 veh/hr/ln which is in line with the results of scenario 6.

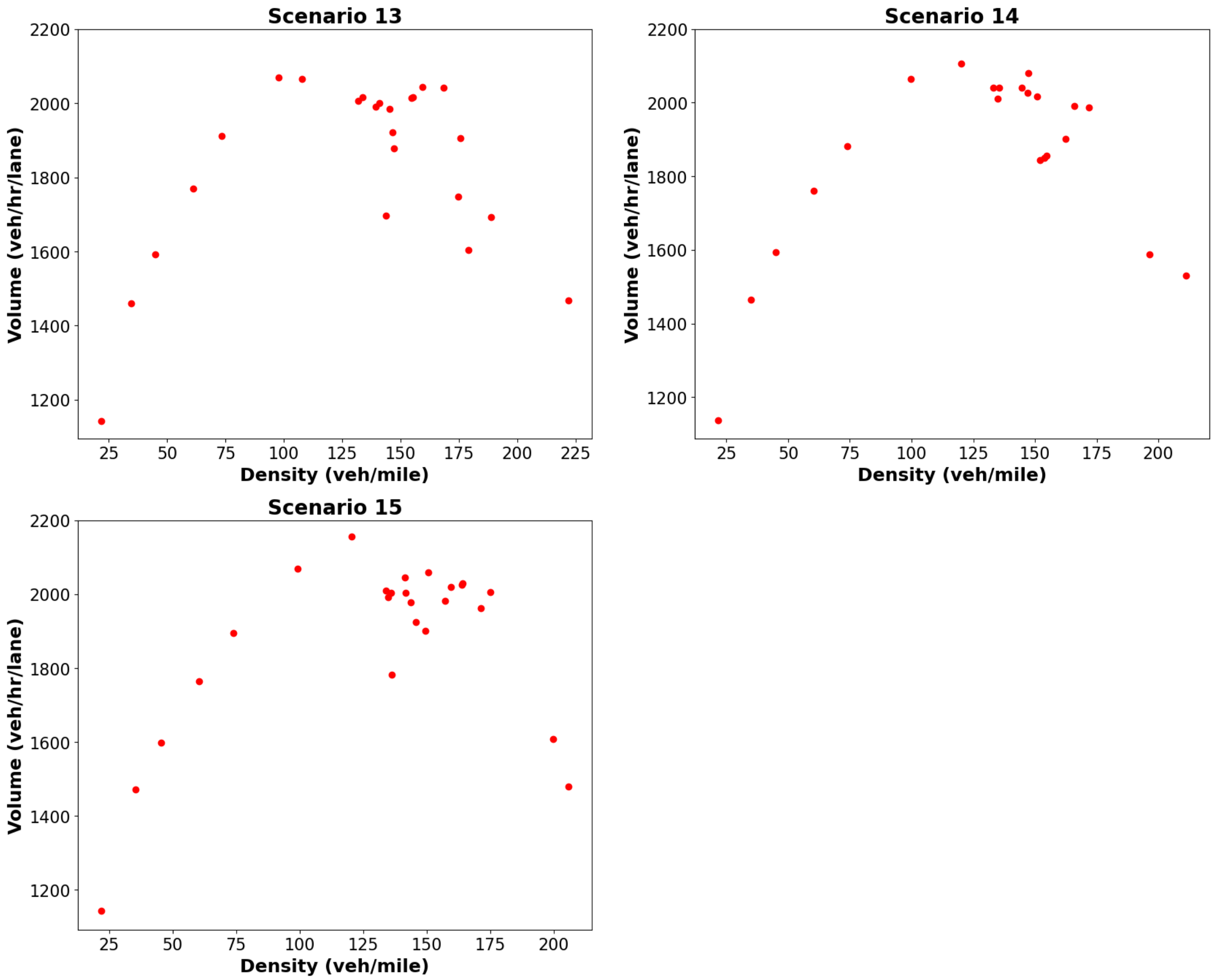


Figure 57 Flow vs Density curve for group 3 scenarios under unrestricted situations

In group 3 analysis has been done for a case where the level 4 AV penetration is high. The results indicated that the capacity improved further, and the highest capacity values close to 2200 veh/hr/ln are observed for scenario 15, as illustrated by Figure 57, where level 4 AVs are at 33 percent. However, the trend of increase can be seen from scenario 13 onwards depicting that as the percentage of highly AVs increases the impact on the capacity increases rapidly.

Overall, it can be comprehended from the analysis that when the presence of partially AVs is higher (up to SAE level 2) maneuvering over an infrastructure that has lower interactions with humans is found to be immensely beneficial. As the penetration of higher AVs augments allowing, it to transition to use complete infrastructure would yield better results as opposed to restricting to a single lane. Further, it is worth noting that certain values adopted while calibrating the model are conservative therefore the capacity values presented here need not be absolute but what is of most significance is the trend of improvement in capacity which is expected to occur irrespectively.

Analysis on Urban Section

With the help of simulation outputs from SUMO, East Bound (EB) and West Bound (WB) traffic along the E Commerce ST and Babcock RD are analyzed for the given peak hour flow and incremental flows of 25%, 50%, 75%, and 100%, respectively.

- Demand 1.00 = PH flow (real-world data)
- Demand 1.25 = PH-flow * 1.25
- Demand 1.50 = PH-flow * 1.50
- Demand 1.75 = PH-flow * 1.75
- Demand 2.00 = PH-flow * 2.00

For the urban corridor, the internal intersections having no traffic light control have not been considered, hence it was rational to measure the performance indicators in terms of average speed, average travel time, and average waiting time rather than capacity. The percentage changes in the traffic performance for various scenarios are discussed in this section for the abovementioned urban corridors.

Analysis for Urban Study Corridor 1: East Commerce Street (TLC Intersection)

The input flow from the EB and WB direction of E Commerce ST for the PH was nearly equal (477 and 426 veh/hour, respectively). However, the flows from the cross-traffic lanes and the turning probabilities were different which caused the variation in speed, travel time, and waiting time for both directions. Hence, they were analyzed separately.

Average Speed (EB and WB)

The figurative representation of the average speed of E Commerce ST is depicted by Figure 58. For both directions of travel, the percent change of average speed increases from the base case. Scenario 6, scenario 9, and scenario 15 are the best scenario in terms of speed improvements in their respective groups. This is due to the higher proportion of the level of automation in these scenarios. The advantage of automation is most perceived by scenario 6 of EB direction whereby the percentage change of speed increased from 17.96% for the base demand to 26.26% for twice the base demand. It is to be noted that, scenarios in which level 3 vehicles were preferred over level 4 vehicles had more or less the same speed improvements over the scenarios in which level 4 vehicles were preferred. This is because, both the level 3 and level 4 vehicles have the same car following and lane changing model parameters and for this study corridor, it is assumed that level 3 vehicles can navigate without any disengagements.

Average Travel Time (EB and WB)

Figure 59 demonstrates the average travel time of EB and WB direction. For EB traffic, base, 125%, and 150% demand shows similar properties. However, at more congested segments, 175%, and 200% demand, the travel time decreases significantly in comparison to the base case. For WB traffic, the base case and various scenarios follow the same pattern for all but 200% demand level. Hence, the advantage of implementation of AVs can be more perceivable during a high level of demand.

Average Waiting Time (EB and WB)

The average waiting time for EB direction is higher than that of WB direction as illustrated by Figure 60. Similar to the average speed and average travel time, the percentage change in the average waiting time for various scenarios in comparison to the base case can be realized more at a higher level of demand for both directions. This measure further supports that AVs perform better in a more congested urban setting.

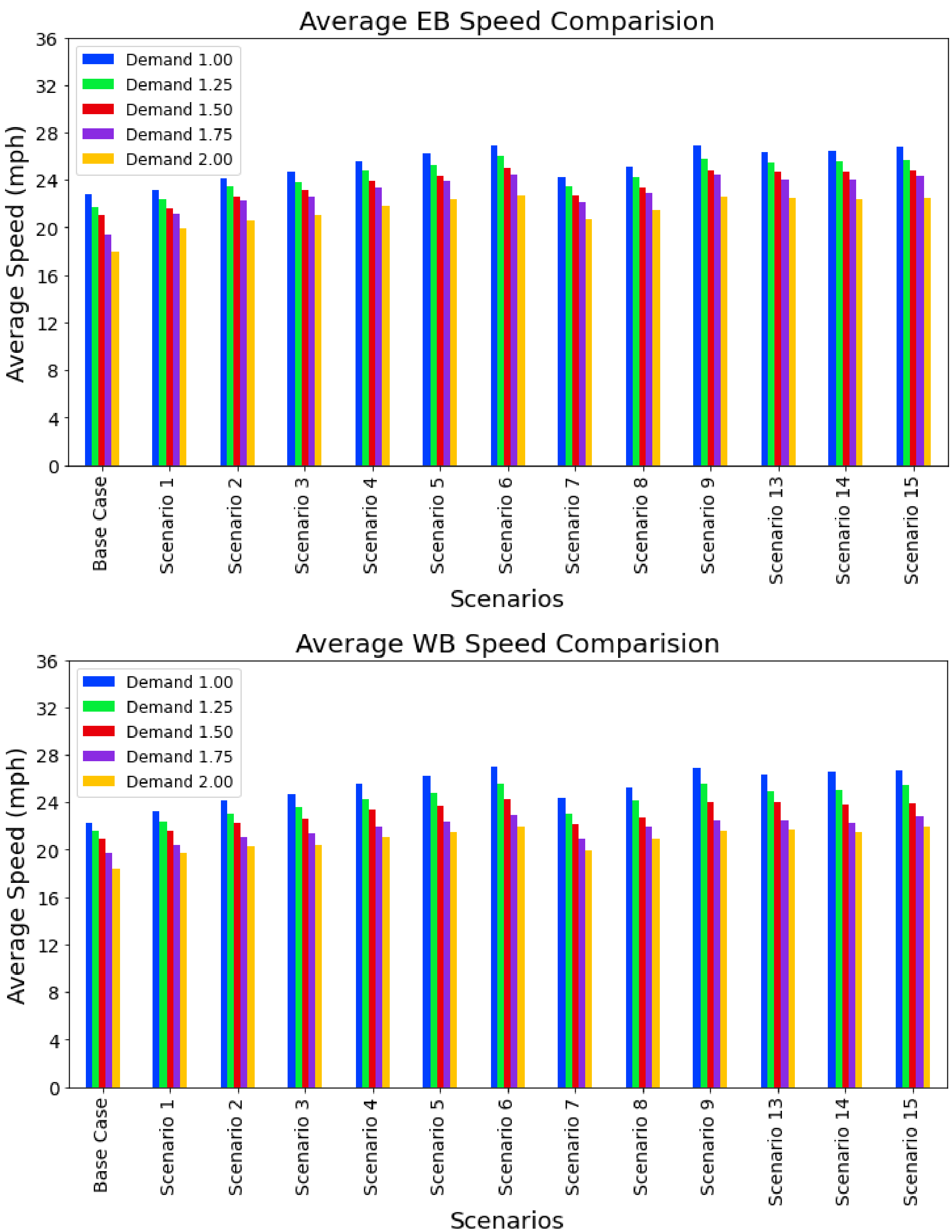
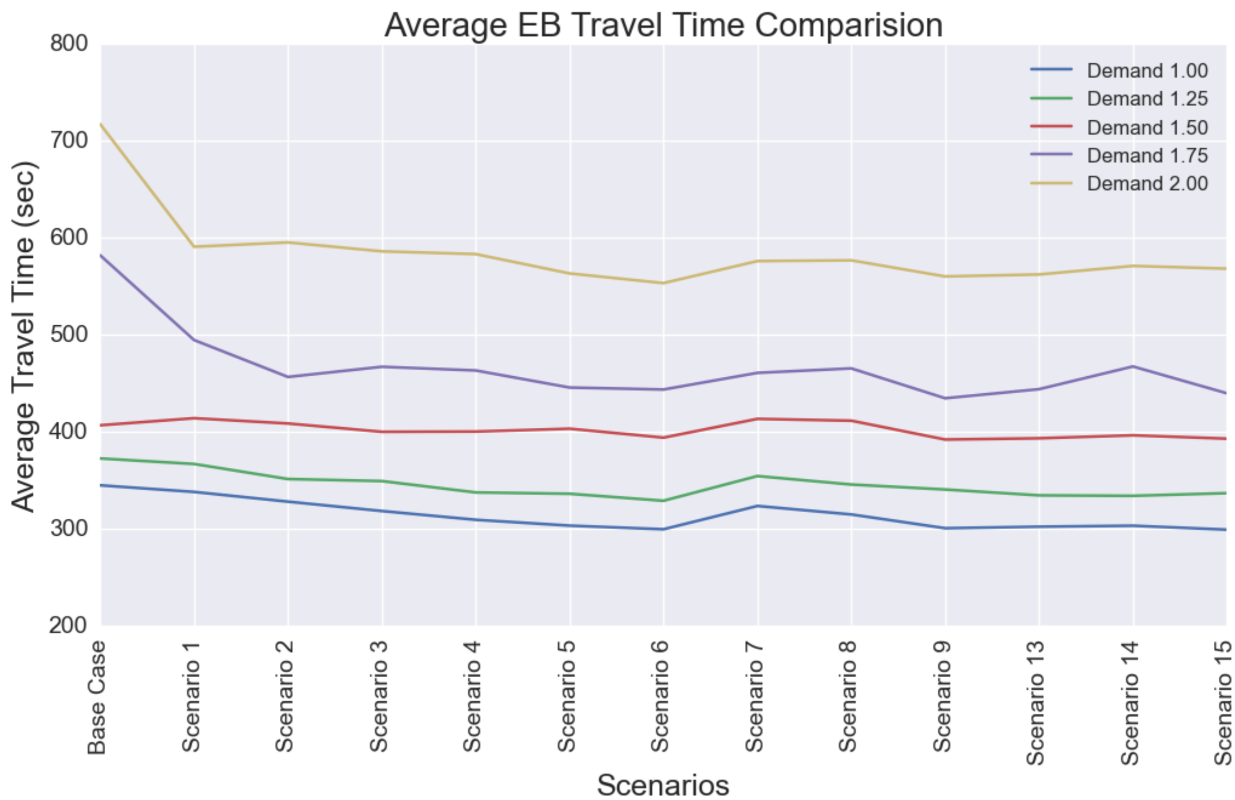


Figure 58 Average speed (mph) EB and WB (E Commerce ST)



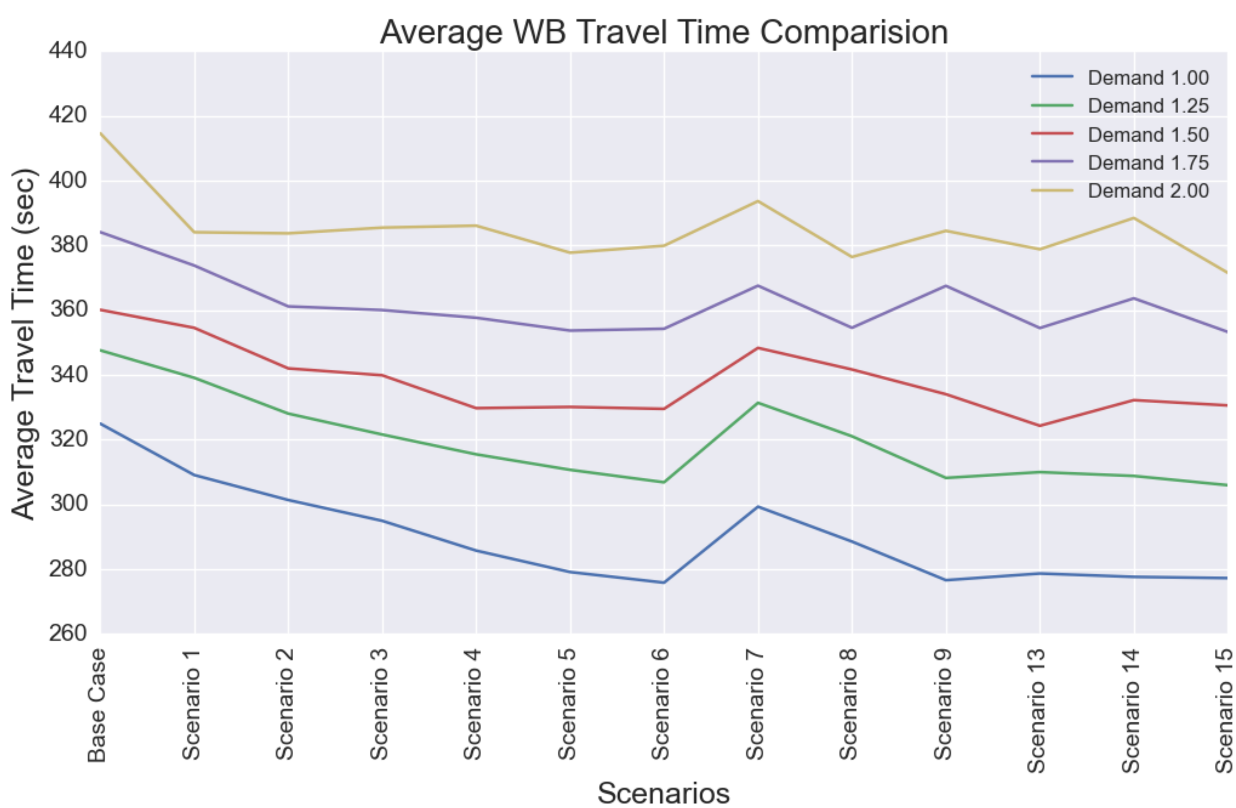
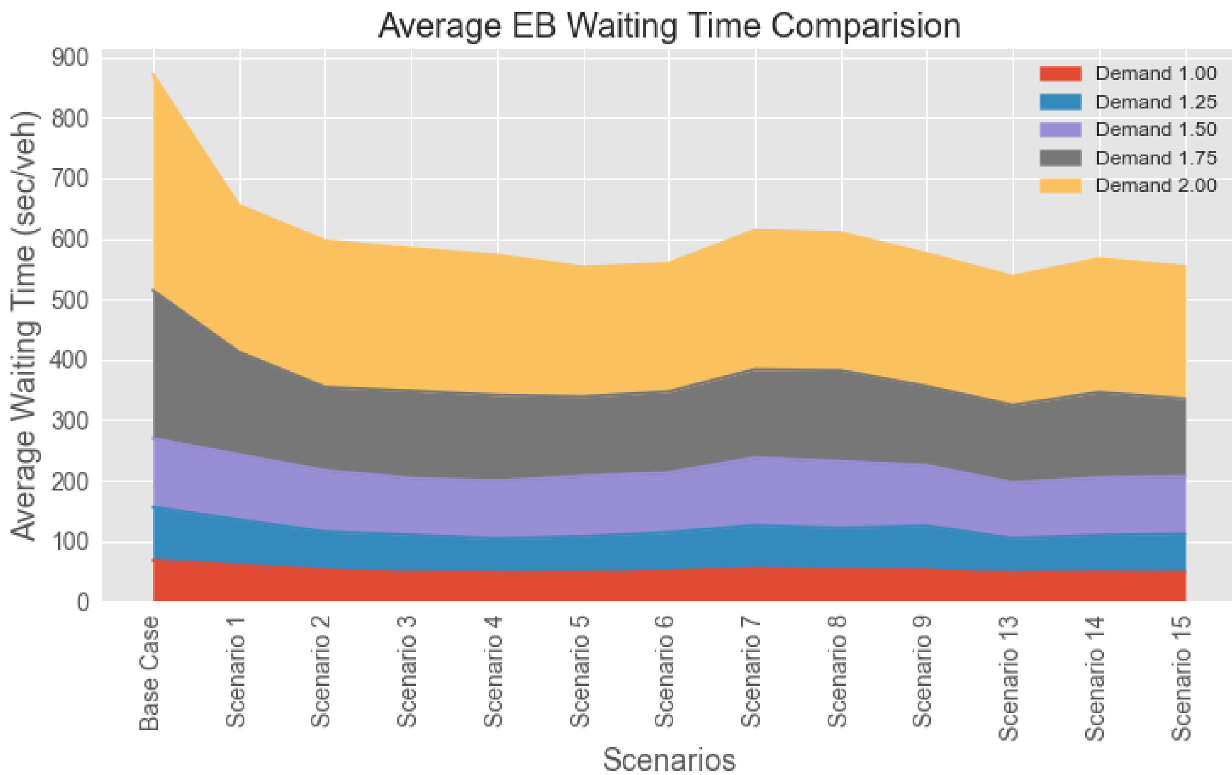


Figure 59 Average travel time (sec) EB and WB (E Commerce ST)



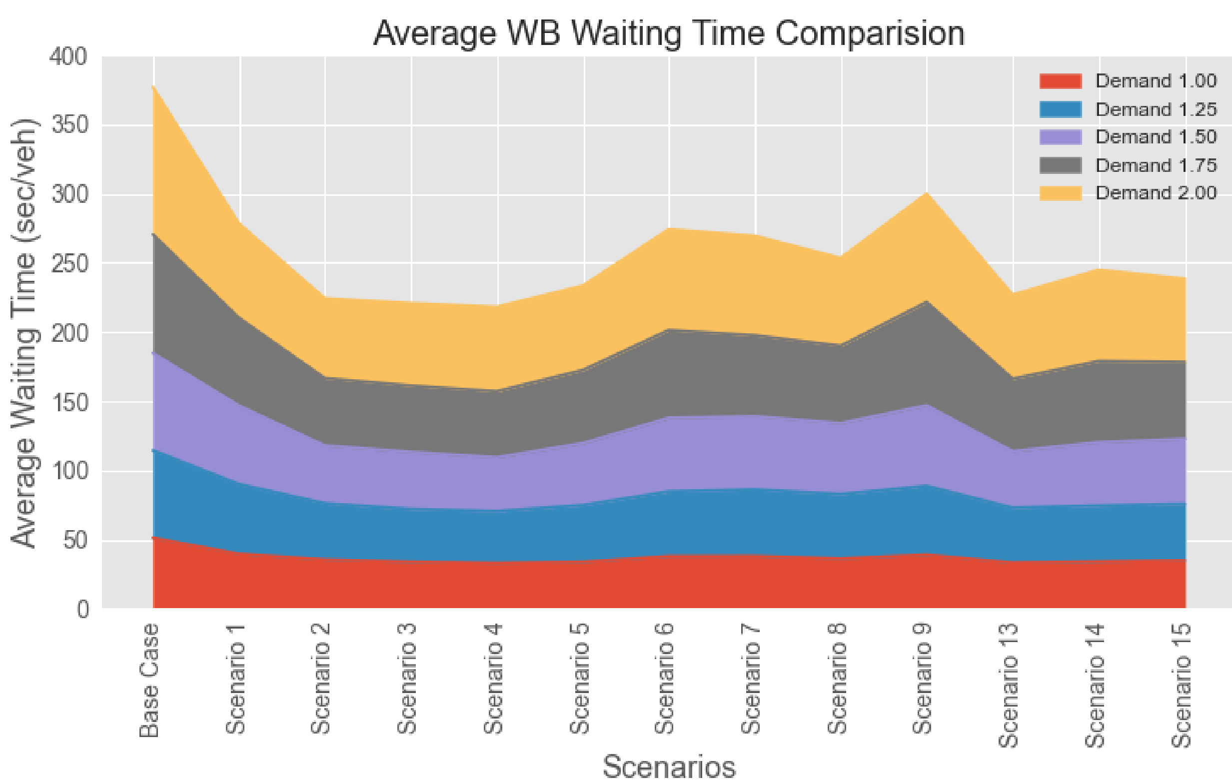


Figure 60 Average waiting time (sec/veh) EB and WB (E Commerce ST)

Analysis for Urban Study Corridor 2: Babcock Road (All Way Stop Intersection)

Unlike the first corridor, the input flow from the EB and WB direction for the PH was significantly different. The EB and WB direction had initial demand of 532 veh/hour and 1265 veh/hour, respectively. Moreover, the flows from the cross-traffic lanes were significantly low in this section having little to no impacts on the concerned corridor. This has caused a significant difference in the pattern of changes that have taken place in terms of average speed, travel time, and waiting time for the various input demands listed below:

- Demand 1.00 = PH flow (real-world data)
- Demand 1.25 = PH-flow * 1.25
- Demand 1.50 = PH-flow * 1.50
- Demand 1.75 = PH-flow * 1.75
- Demand 2.00 = PH-flow * 2.00

Babcock RD corridor consists of two TLC intersections and one all way stop intersection. It is assumed that level 3 vehicles will disengage and give the control back to humans. In that, it switched to level 2 vehicles. The disengagement distance is based on take over time (*271*) and the speed limit of the corridor. It is calculated as follows:

Distance to disengagement = (take over time) * (speed limit of an edge)

= 10 sec * 30 mph

= 440 ft

Once all way stop is navigated in level 2 driving mode, the human driver gives the control back to level 3 AVs at the same distance (440 ft) from the intersection.

Average Speed (EB and WB)

In this corridor, for the peak hour, the EB traffic is less than half of the westbound traffic and even if the input demand is increased to 200% it is lower than the base demand for WB traffic. Figure 61 illustrates the average speed for both directions of travel for various input demands. Due to lower input demands in EB direction, the improvements owing to automation driving might not be visible. This statement is further aided by the input flow of PH, and 125% for the WB direction. However, when the demand increases to 175%, there is a significant drop in the average speed of HDVs, and improvements in the average speed for AVs is noticeable in each of the three groups. This occurs because when the demand is low, the HDVs usually drive at a speed higher than the posted speed limit. This will cancel out the benefits that can occur due to lower following distance and lane changing behaviors of AVs.

Another observation can be made at 150% demand for WB traffic: the corridor for scenarios having a higher percentage of level 3 vehicles has a comparatively lower speed. At this demand level, the disengagement might be causing a fall in the speed performance of the corridor. However, when the demand is further increased, the base case gets congested and the average speed plummets down (falls from 22 mph to 14 mph). For this increased demand level, the performance of scenarios having a higher proportion of AVs is better. Hence, it can be concluded that the advantages of AVs are more applicable to cases when the base model incurs a high flow of input demand.

Average Travel Time (EB and WB)

Figure 62 demonstrates the average travel time of EB and WB direction. Similar to the average speed, the benefit of automation is more visible for higher demands of WB traffic. That is, for 175% and 200% demand, the average travel time improves from 723 sec for base case to 496 sec for scenario 6 of group 1, 503 sec for scenario 9 of group 2, and 507 for scenario 14 of group 3. For EB traffic, a similar trend is observed for all the demands levels. The average travel time is capped between 245 sec to 280 sec.

The consequences of implementing disengagement for level 3 vehicles at all way stop intersection are visible for 150% demand for WB scenario. The travel time for the scenario having a larger proportion of level 3 vehicles is comparatively higher. The disengagement might be the causing factor for the reduction in the performance of the corridor at 150% demand. However, as the demand is further increased, the base case gets congested, and the advantage of automation is clearly visible.

Average Waiting Time (EB and WB)

Figure 63 shows the average waiting time for EB and WB traffic. For EB traffic, since no congestion occurs even at 200% demand, the waiting time is low and almost equal for the base case and all the scenarios. However, for WB traffic at 150% flow, the waiting time for scenarios having a higher proportion of level 3 (scenario 6, 9, and 14 for their respective group) increases. This might have occurred due to the disengagement of level 3 vehicles. Moreover, like average speed and average travel time, the average waiting time starts showing improvement once the demand is further increased (175% and 200%).

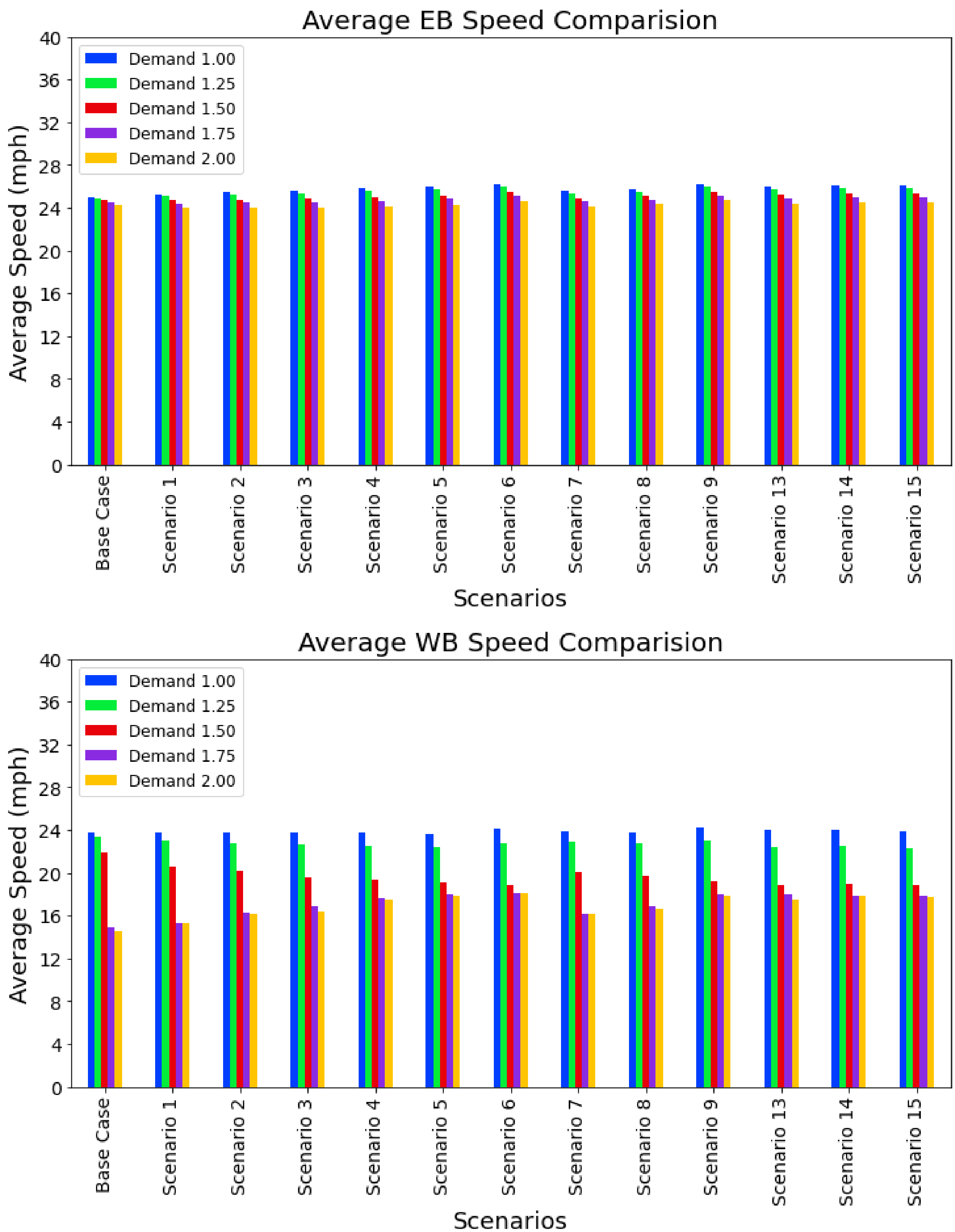
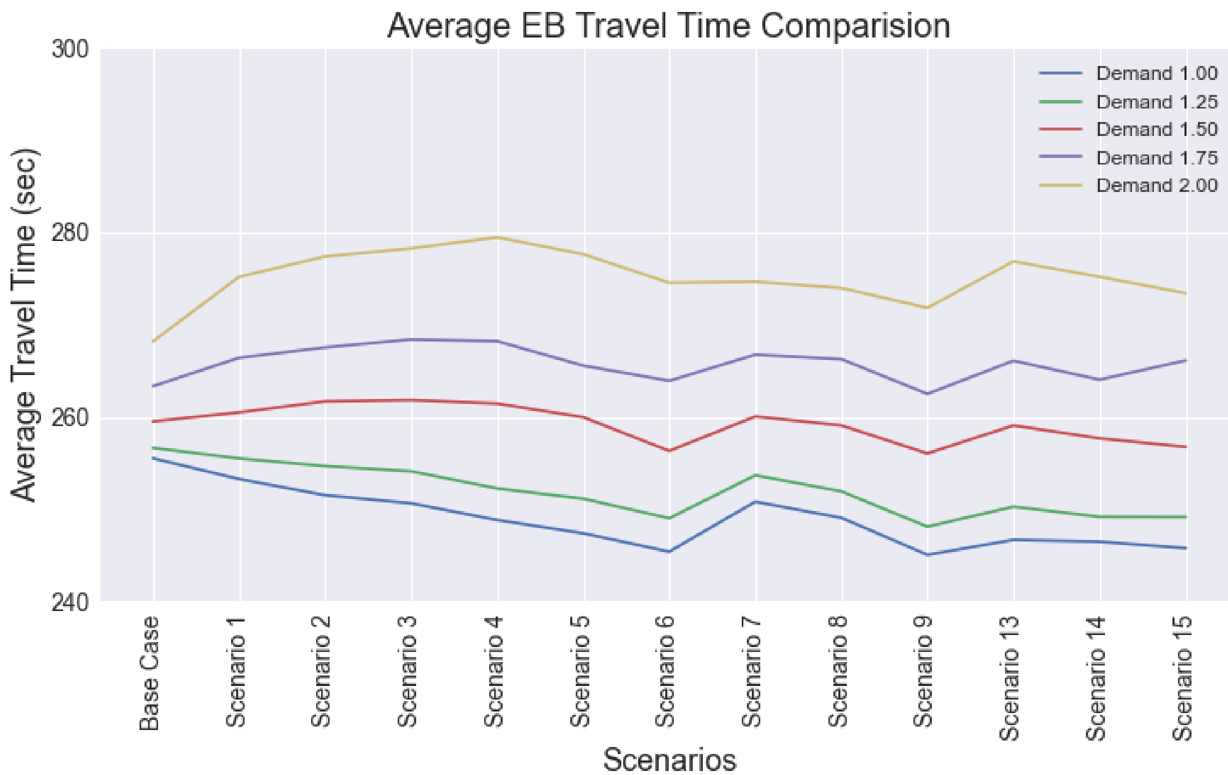


Figure 61 Average speed (mph) EB and WB (Babcock RD)



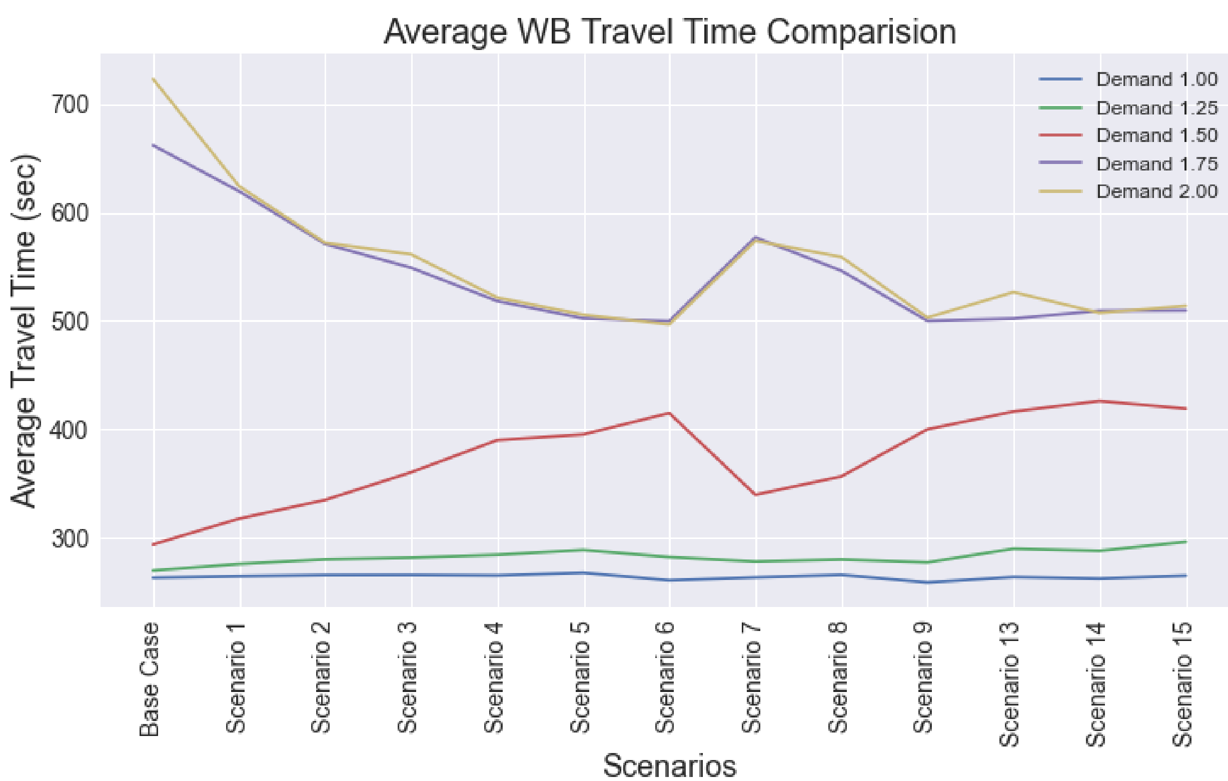
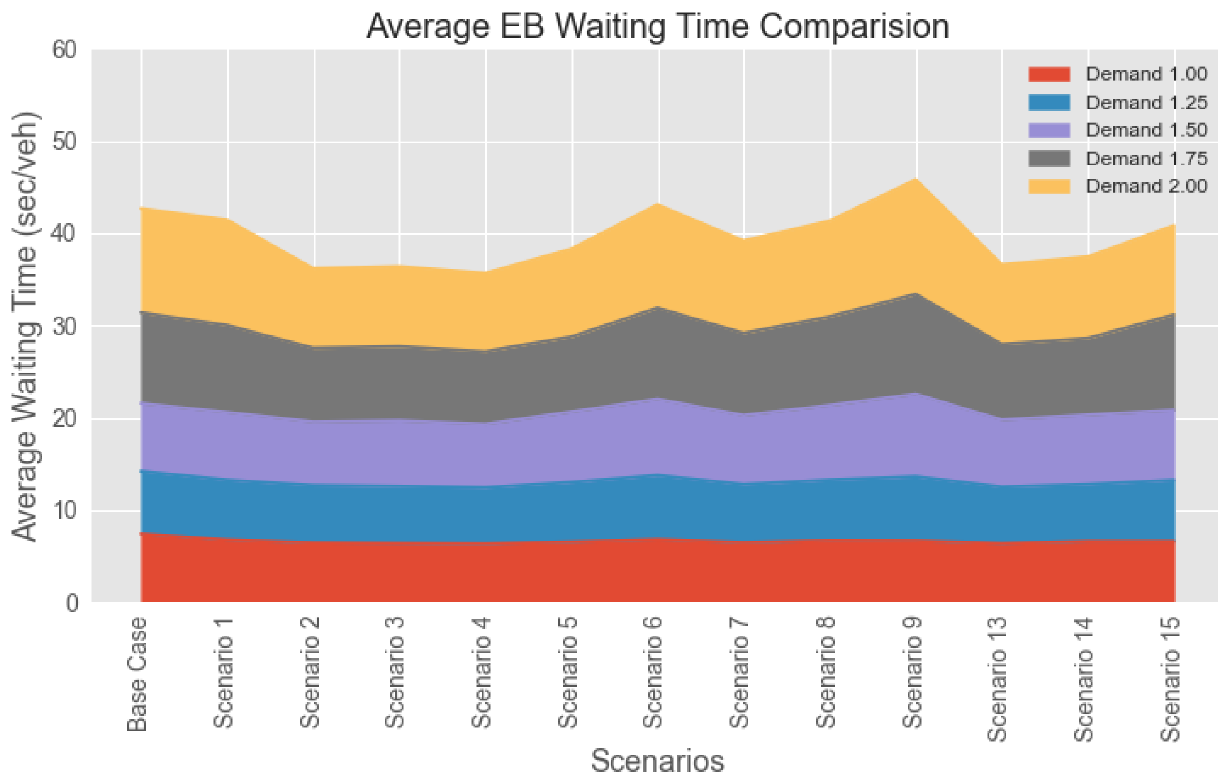


Figure 62 Average travel time (sec) EB and WB (Babcock RD)



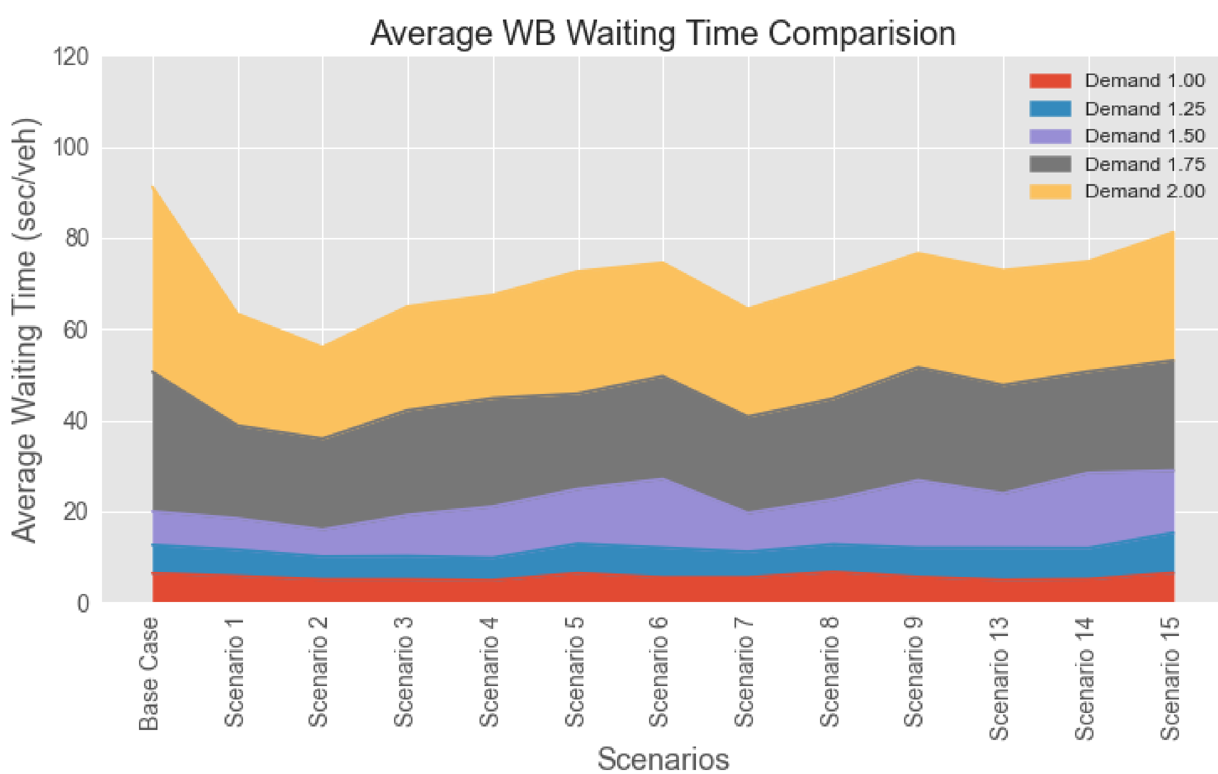


Figure 63 Average waiting time (sec/veh) EB and WB (Babcock RD)

Summary

The primary goal of the study was to investigate the impacts different SAE levels can have on the capacity and traffic performance of a corridor. For this purpose, two conditions on the freeway segment were considered. The first analysis limited AVs to HOV lanes while the second analysis examined the modifications in capacity when AVs are unrestricted to use any lane. In the urban segment traffic performance of two different corridors was explored. The first corridor considered six TLC intersections while the second corridor contained a combination of TLC intersections and an all-way stop controlled intersection.

Results of the analysis for freeway corridors revealed that capacity is found to improve significantly when AVs start to maneuver on the roads. In the first analysis when AVs were restricted to use HOV lanes, the capacity increased nearly 15% when the combined share of SAE level 1 and 2 vehicles were close to 60 percent as given in scenario 2. Following that the increase in capacity due to automation was subjugated by the increase in flow consequently resulting in the reduction of capacity values for later scenarios. In the second analysis, allowing AVs to use all travel lanes provided encouraging results with capacity improving up to 21 percent. Overall, it can be concluded that capacity improvements are profound when “nearly dedicated” lanes are utilized by partially AVs. On the other hand, when conditional and high automation level vehicles exist (SAE level 3 and above) in high proportion, utilization of full travel lanes has noteworthy improvement in capacity.

Two different types of urban corridors were analyzed in this study. One with only the traffic-light controlled intersection and the other with a combination of traffic light and all way stop intersection. The traffic performance was measured in terms of average speed, average travel time, and average waiting time per vehicle for the whole corridor. Results from the first corridor (East Commerce St) showed improvement even at the base demand. And as the demand increased the performance of scenarios having a higher proportion of AVs also increased. In the second corridor, disengagement of level 3 vehicles at “all way stop” was considered in which a level 3 vehicle would switch its control back to human while maneuvering through an all way intersection. This might have caused a dip in performance at 150% demand. However, when the demand is further increased (175% and 200%), the scenarios with a higher percentage of AVs perform better.

It is worth highlighting that the model used in our study is conservative in certain situations especially the level of co-operation is assumed to be low as compared with human-driven vehicles, this is defensible since at initial stages the AVs still behave conservatively. Further, the automation is assumed to take place only in passenger cars thereby limiting the percentage of penetration to only 50 percent of traffic in freeways even though complete automation is assumed. Further, the ACC model is expected to have instability at higher penetration levels, with most of the scenarios having vehicles that use the ACC model, which could be a factor for high improvement in the capacity as one would expect (*255*). The outcomes of this study shall be utilized in the upcoming tasks for recommending various design modifications.

An important limitation of this study is that truck platooning has not been considered in this study. Truck platooning is an important policy question, and the policy of various state are different. Some states allow it while some do not. The maximum size of the platooning is also not standardized. Moreover, truck platooning can deteriorate the pavement and bridges at an extensive rate. The tradeoff between energy saving through truck platooning and infrastructure retrofitting to sustain platooning needs to be analyzed that can be an interesting extension of this project. On the other hand, passenger car platooning does not have high impacts on pavement and has been incorporated in the microsimulation model in this project (although model in this study allows a conservative time headway, more aggressive approach may be adopted at very high market penetration of CAV). The dedicated lane for trucks is also not considered in this project. Trucks typically use right lane and dedicating right for trucks may act as physical barrier for right turning vehicles especially when truck platoon size is large. The project evaluates multiple scenarios with dedicated lanes for autonomous passenger cars. Dedicating lanes for AV may be useful from transportation electrification perspective where dedicated lane can be facilitated as charging lane with static or dynamic wireless charging infrastructure for autonomous vehicles (trucks, cars, or buses) which are most likely be electric. However, determining optimal configuration and location of charging lane will be separate research project in itself.

CHAPTER 6: CONCEIVE INNOVATIVE ROAD DESIGN UNDER AV SCENARIOS

Introduction

The optimal operation of AV depends upon multiple factors. Ideal road and communication infrastructure are critical for the efficient operation of AVs. This chapter primarily focuses upon the road infrastructure elements. It starts by defining the methodology adopted, followed by the findings and recommendations. During the course of the project, various domains of AV and roadway infrastructure elements were shortlisted based on past studies and findings. Before we go to the innovative road elements it is imperative first, to explain the operation of AVs.

How do AVs Work?

Perception: As human-driven vehicles, AVs also require observation of environment around them, whether they are looking ahead for traffic signals or road markings. This is done by perception, which helps the car to see, recognize, classify, and evaluate the things around it.

For an AV to make informed decisions, it needs to perceive traffic lights, road markings, roadside barriers, pedestrians, etc. The following sensors help AV to make informed decisions:

- Camera: The camera provides a high-resolution representation of its environment. It enables AV to perform multiple tasks such as: classification, segmentation, and localization (*272*). Multiple cameras (left, right, front, and back) can be used together to get a 360-degree view of the entire environment. Both long-range and short-range views can be captured by the cameras. However, during extreme weather conditions like heavy rain, fog, snow, and poor lighting (especially at nighttime) cameras capture noise that can lead to discrepancies and poor performance. Moreover, the visual data from cameras need to be further processed to measure the distance of the object (*273*).
- Light Detection and Ranging (Lidar): It uses laser light pulses to measure the distance between objects by determining the time taken by the laser light to return to the receiver after it gets reflected off surfaces. Lidar can provide higher resolution imaging than Radar but is expensive and does not function well in heavy rain and fog.
- Radio Detection and Ranging (Radar): It calculates the distance between objects by using radio waves. They are highly effective as radio waves can be used in any weather conditions. However, radars are low-resolution sensors and are sensitive to noise. The data from radars should be cleaned before making informed decisions.

A figurative difference of how camera, lidar, and radar see objects is shown in Figure 64.

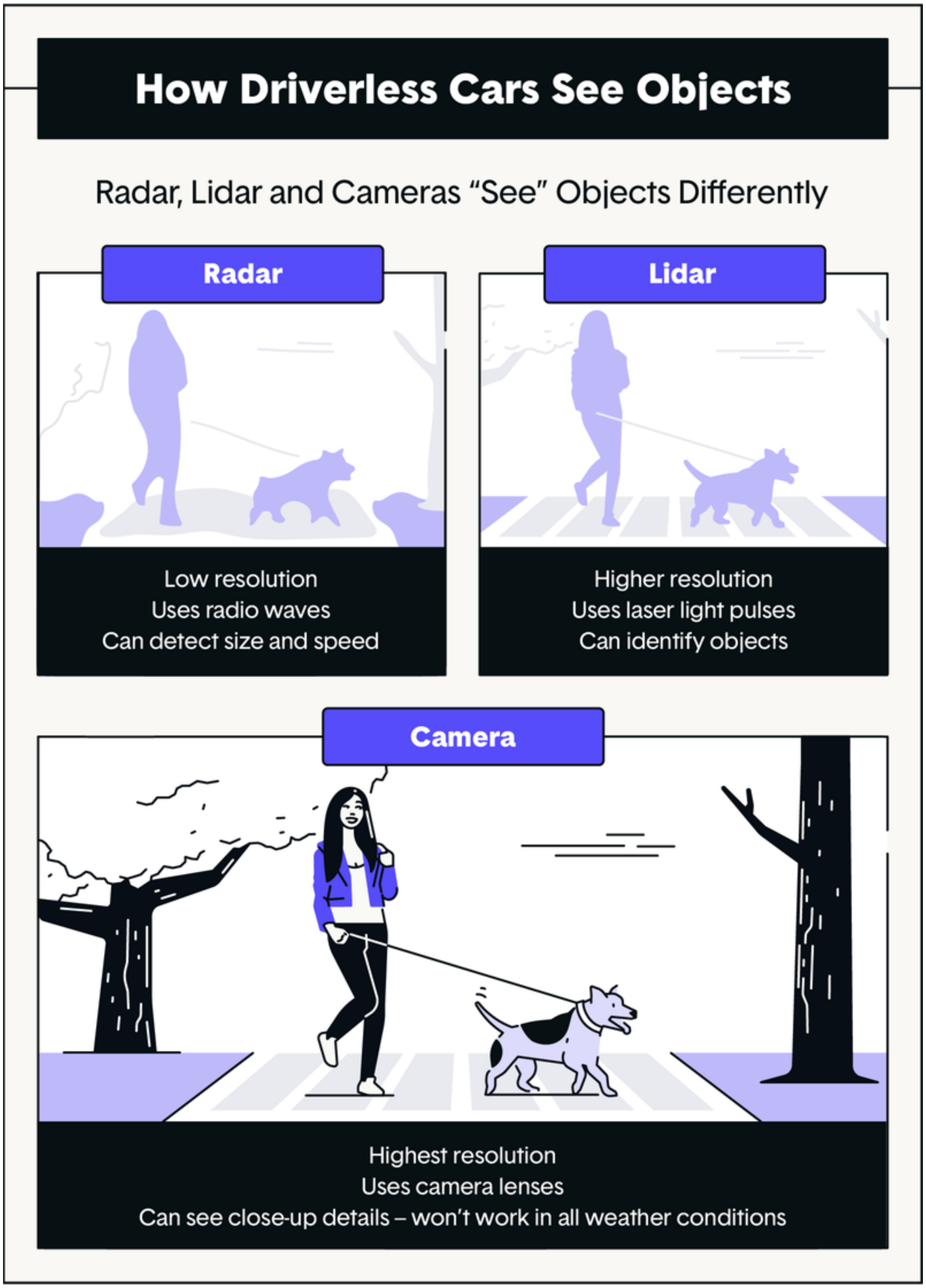


Figure 64 How AVs see objects

Source: The Zebra (*273*)

In addition to the camera, lidar, and radar, complementary sensors such as microphones enable the car to pick up audio (emergency sirens) from its environment.

Localization: Localization in AV is a process of determining the position and orientation of the vehicle in the real world so that it can make informed decisions on how to navigate from point A to point B. It can be thought like the GPS on our phone. Localization is also referred to as Visual Odometry (VO) which works by matching key points in consecutive video frames. It helps to identify and classify roads, pedestrians, markings, and other objects around. Deep learning (neural network) is generally used to improve the performance of VO.

Prediction: Understanding the behavior of human drivers involves emotion rather than logic. It is a complex task. While commuting from one point to another, there will be numerous instances where the driver has to predict the next action of other vehicles and pedestrians. In case of AVs, once all the information is perceived and captured by the sensors, it gets processed. With the aid of deep learning algorithms, all the possible reactions of road users can be predicted. The next step is to choose the correct action out of a finite number of possibilities.

Decision Making: Decision making is one of the vital parts of AVs. In an environment, where there are uncertainties, a dynamic and precise system is required. It must account for the fact that not all sensor readings will be accurate, and that humans can make erratic decisions while driving that can impact AVs in mixed traffic. Deep reinforcement learning algorithms (Markov decision process along with Bayesian optimization) can be used for decision making. As shown in Figure 65, it involves the following steps (*272*):

- Path or route planning: It is the primary step of decision making. The car should select the optimal route from its current position to its destination.
- Behavior arbitration: Static information, like roads, intersections, average travel time etc. are known beforehand. However, the dynamic behavior of road users which can change throughout the journey is unknown. Markov decision process helps in solving this problem.
- Motion planning: This includes motions such as the speed of the vehicle, car-following, lane-changing etc. that must be feasible and comfortable for the passengers.
- Vehicle control: This is the process of execution of the reference path from the motion planning system.

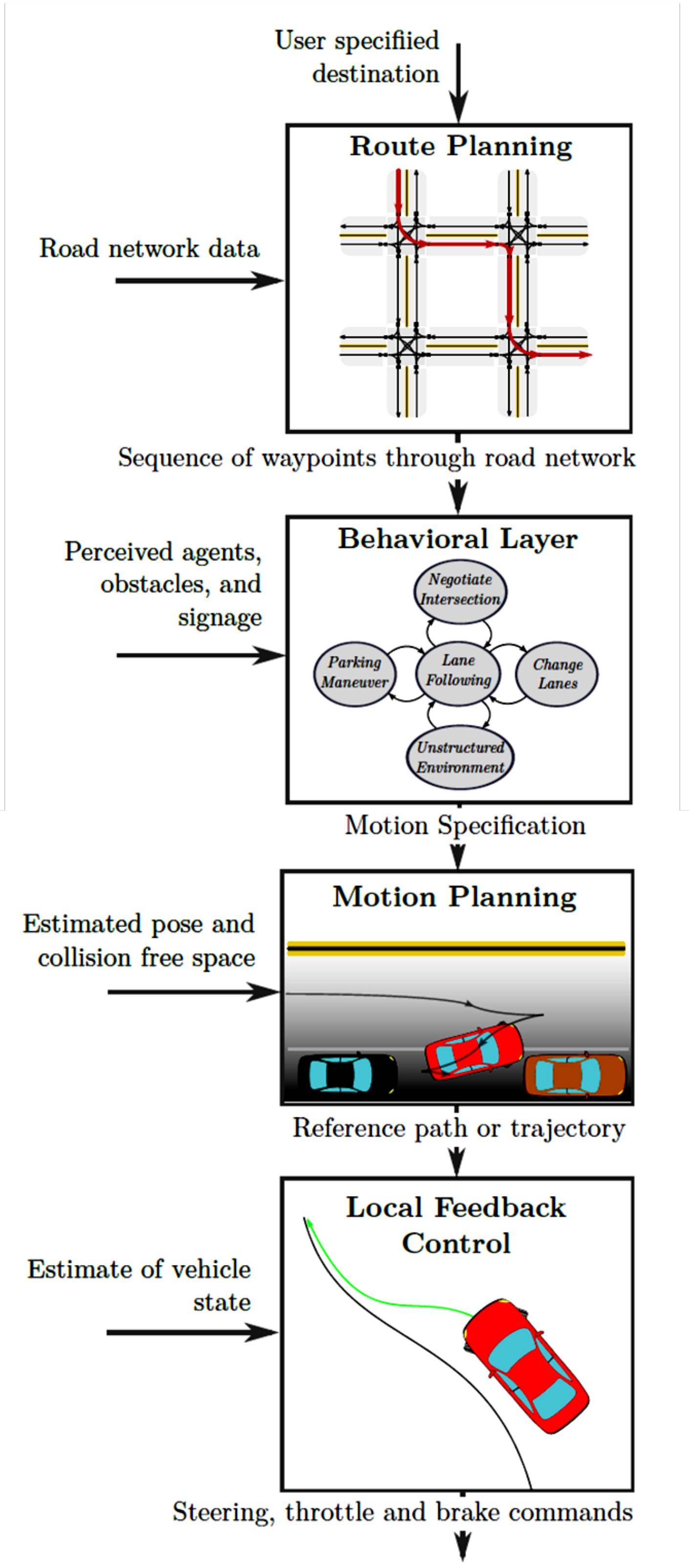


Figure 65 Steps involved in decision making. Source: Paden et al. (*274*)

Further, Figure 66 depicts an overview of AV system and associated workflows, and Table 48 demonstrates the scope and dependency on infrastructure for each component of the AV system.

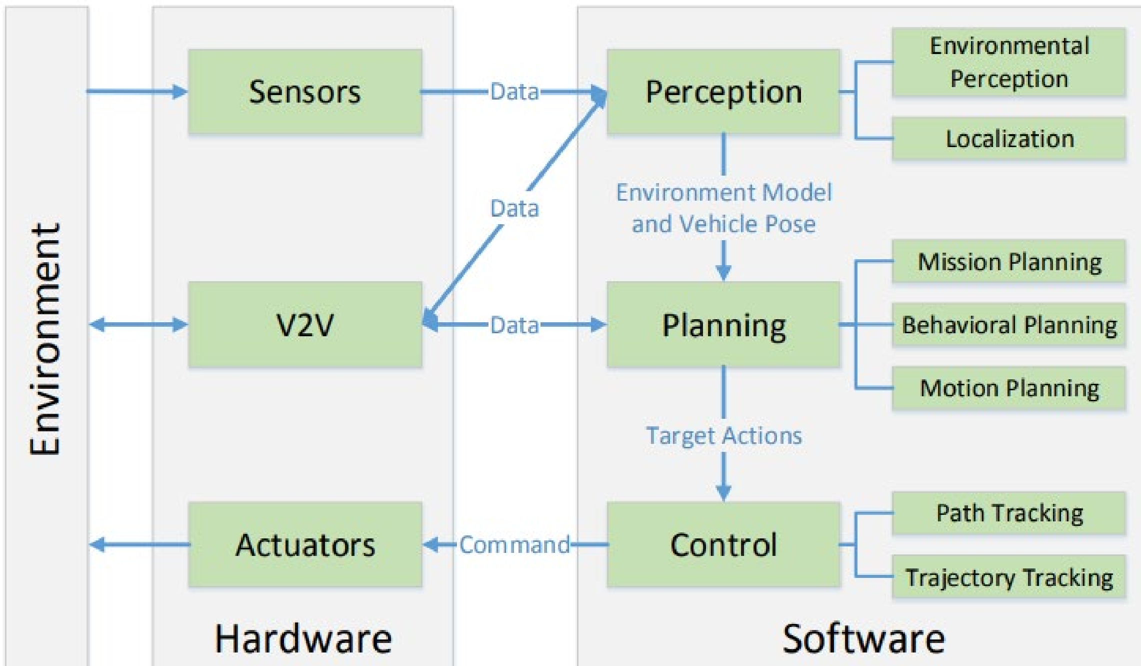


Figure 66 Depicting AV system along with its components. Source: Pendleton et.al (*275*)

Table 48 Infrastructure dependency for various AV components

S.N.	AV component	Scope for Infrastructure operators	Infrastructure Dependency
1	Localization	Low	Low
2	Environmental Perception	High	High
3	Mission Planning	Moderate	Moderate
4	Behavioral Planning	Low	Low
5	Motion Planning	Low	Low to moderate

Methodology

The current study considered the opinions of experts in the domain to make suitable conclusions about the concerned topic and derive recommendations. The gathering of expert opinions was carried out in two approaches. At first, a request for a video interview over a telecommunication platform was made after checking for the individual's availability, and for those individuals who were unavailable for the video interview, a web-based questionnaire was shared. The current study made efforts to approach the experts in all domains that are associated with development to deployment of AVs on road. The rationale behind such a method can be easily justified considering the interdependency of different entities such as IOOs, AV software developers, regulatory bodies, planning agencies, Original Equipment Manufacturers (OEMs), non-profit organizations, and many more. Considering the plethora of diversity involved in deploying an AV onto the road, efforts were made to represent as many bodies as possible with some priority to the AV developers/OEMs. This is particularly important in understanding the extent to which any desired change can be made to address the challenges AV might face in mixed traffic situations. In addition, there is always associated tradeoff between what can be done versus what needs to be done. Considering such limitations, a representative group of experts was gathered in the current study.

Questionnaire

After performing an extensive literature review especially after exploring the recently concluded studies from FHWA (*276*), Caltrans (*277*) and disengagement report (*278*) an initial set of questions was formulated. This was followed by pilot survey in which initial set of questions was circulated among 5 academicians in the performing organization for their feedback on the survey. Based on the feedback received on the readability and extent of topics covered, the questionnaire was revised. After Institutional Review Board (IRB) review, the developed questionnaire was published on the Qualtrics platform and utilized in subsequent stages. Even though the primary approach was to contact individuals through telecommunication-based video interviews, having an online version of questionnaire was considered a good redundancy to possess. Some experts preferred to enter their response through online questionnaire than video interviews. The questionnaire consisted of 25 questions covering the majority of the aspects that are appropriate in the AV future, complete set of questions can be found in Appendix 1 (*279*).

Participants

Subsequent to developing the questionnaire, the next stage was to identify a group of experts for this study. As an initial step to obtain the list of AV experts, the California disengagement report (*278*) was examined to identify various AV operating/testing mobility companies. In addition, a list of OEMs, mapping companies, algorithm developers, and connectivity-oriented companies was identified. On the other hand, from the infrastructure side, several individuals from IOOs, DOTs, city councils, CAV task forces, and planners were identified. Along with the above entities research institutes, and non-profit organizations (NPOs) that primarily work alongside AV developers were identified for the study. Identified individuals were contacted through email or professional networking platforms. Initial communications made were associated with a cover letter that briefly explained the scope of the project, and how the contacted individual's expertise is related to the current project. Upon the expression of interest from contacted individuals, they were presented with two alternatives to contribute to the study. At first, they were asked about their availability for the video interview session. If respondents could not participate in the video session due to time constraints, a link to the web-based questionnaire form was shared that provided them the flexibility to enter the response as per their convenience.

As shown in Figure 67, 110 experts from different domains were contacted either through email or social media platforms. Among the contacted individuals 22 respondents agreed to take part in the interview and 13 initially agreed to take the questionnaire survey. Upon sending the questionnaire, 7 participants did not respond. Therefore, overall, 28 participants participated in the expert opinion study.

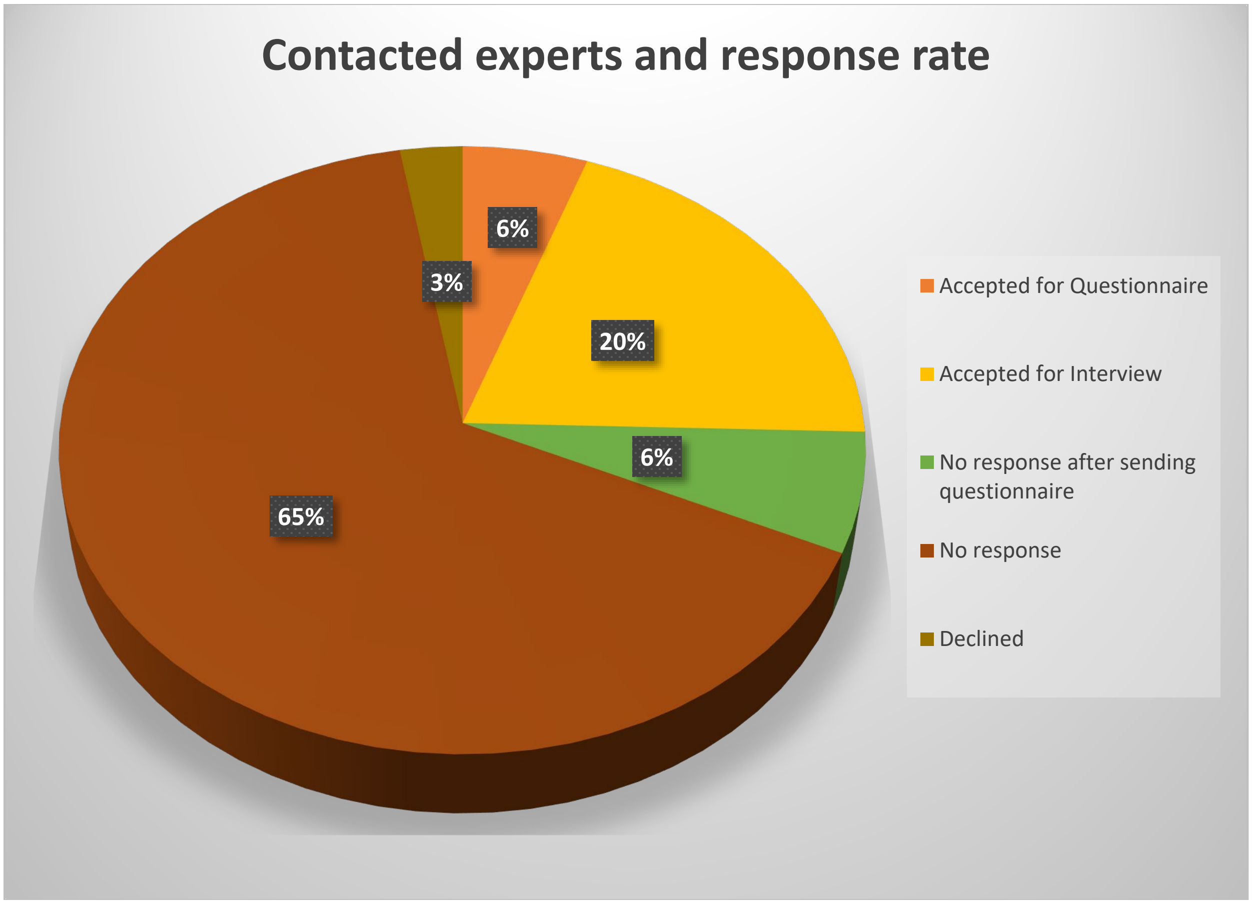


Figure 67 Count of approached experts and participants

Ensuring diversity, the final list of participants was as represented in Figure 68. The majority of the respondents were from

- AV industry startups - 8
- Research institutes, DOTs - 4 each
- Academicians, AV/CAV task force - 3 each
- NCUTCD committee, NPOs, Transportation firms - 2 each

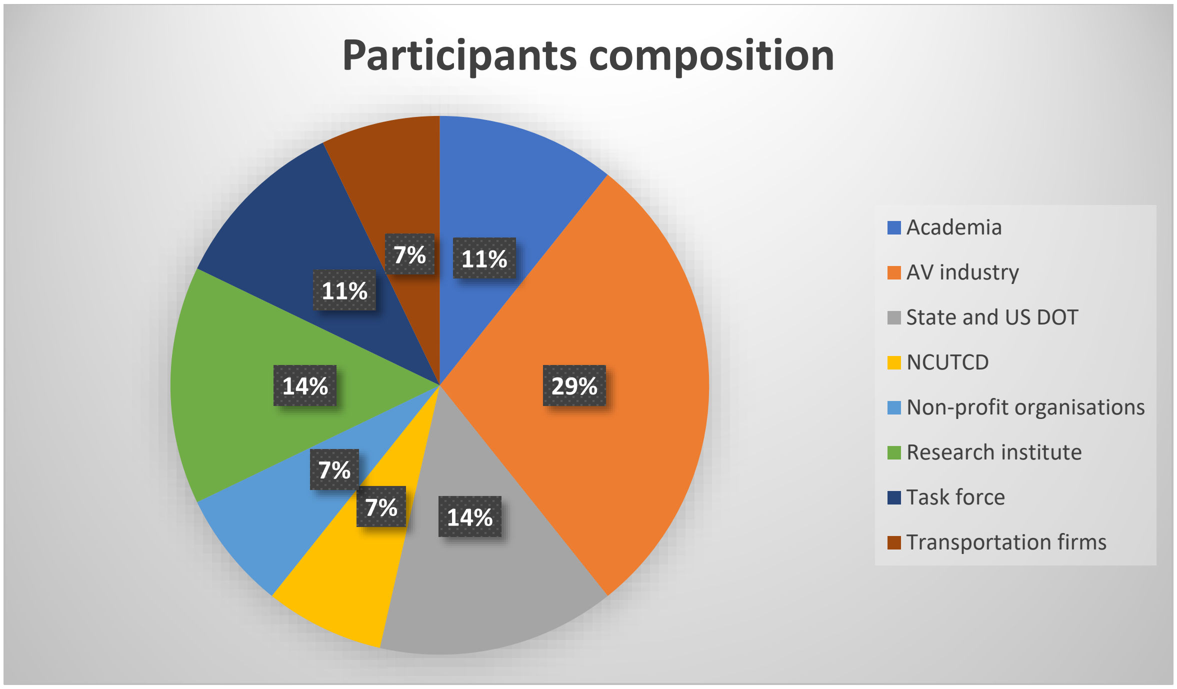


Figure 68 Composition of participants

Approach

For the video interview, a brief context of the study was described especially highlighting the goals of the project. Then published questionnaire was projected on the device for better interpretation among the participants, especially for those questions that had figures to improve the perception. With the permission of the participants, all the interviews were recorded for analysis, and it was assured that the responses received shall remain anonymous and responses shall be analyzed and reported without revealing the identity of the participants. Further during the interview, each question was articulated to participants and was further elaborated when needed.

For the web-based survey responses since it is self-administered an interactive approach could not be mustered. Most of the questions were open-ended allowing the participants to elaborate as detailed as possible, for those questions that were left unanswered an effort was made to reach the participant again and obtain the response.

Analysis

After gathering opinions both through interviews and online surveys, the next step was to transcribe the recorded video responses. Transcription was done by rerunning the recorded interview simultaneously screening the identity of the participants. Similarly, the responses recorded through a web-based platform were deidentified and used in subsequent analysis. The analysis was carried out in the order in which the questions were asked. Responses from each participant were interpreted for a specified question and then the findings were reported. These obtained findings braced with the findings from literature (if available) led to the development of recommendations in this report. Those respondents who had limited knowledge of a particular asked question were ignored in reporting findings and subsequently in the development of recommendations.

Findings

General

AV is an emerging technology that has the potential to disrupt the way we travel. AVs can sense their surroundings and drive without or with minimum human involvement. For driver assistance, and conditional and partial automation (level 3 and below), a fallback-ready user is vital, whereas for high and full automation (levels 4 and 5), they are not required (*280*). In respect to the growth of AVs, there has been slow but steady advancements. Most new automobiles today come equipped with some type of driver-assistance technology aimed at improving safety (*281*). In the real world, AVs function with the aid of sensors, actuators, complex algorithms, machine learning systems, powerful processors, and high-definition maps (*282*).

The opinions of the AV community on how AVs are operating in real world and the challenges associated with them are listed below:

- AVs are in their infancy. Currently, they are operated in a controlled, low speed, geofenced, and ODD restricted environment.
- AVs operate with the help of on-vehicle sensors, detailed maps, and external information abiding by the defined traffic rules.
- Early adopters of AVs:
    - Autonomous ride services: Simpler revenue generation.
    - Long-haul trucking (hub to hub): Lack of drivers and less challenge of true mixed traffic.
    - Autonomous home delivery: Simpler business model and easier safety issues.
- Higher levels of AVs (level 3 and above) are not yet ready to hit the road.
- Currently in the early stages, when there is low market penetration of AVs, they operate with the primary objective of safety. The true benefits/downsides of AVs are yet to be known.
- AVs are used as a real-time data provider for transportation system management and structure.
- Some of the major challenges for AVs are:
    - Lower market penetration,
    - Maneuvering parking lots,
    - Limited night vision and intelligence,
    - Vulnerable to adverse weather conditions (rainfall and snow),
    - Lack of surrounding judgments (cannot hear accurately while driving, cannot feel the rumble stripes, etc.), and
    - Absence of behavioral judgment.

Pavement Markings

Numerous studies have identified the importance of pavement markings in machine vision and various factors that influence them. A report from Caltrans (*277*) has provided a review of literature related to pavement markings. It has recognized the following factors to be critical in machine vision system:

Characteristics of Pavement markings

- Color of pavement markings,
- Width of markings (4-inch vs 6 inch),
- Type of markings {Standard vs contrast (4-inch with 2-inch marking on either side),

- Retro-reflectivity (commonly achieved by embedded glass or ceramic beads),
- Luminance contrast of lane markings.

Characteristics of the Roadway Surface

- Pavement ruts, potholes, cracks, etc.,
- Undulatory levels of surface,
- Uniformity of surface,
- Visibility of markings under wet or dry conditions,
- Visibility of markings based on the time of the day.

Environmental Factors

- Weather conditions such as snow, fog, rain, etc.,
- Glare from oncoming vehicles,
- Glare caused due to sunlight,
- Atmospheric conditions (sunny, cloudy, foggy, etc.),
- Shadows due to adjacent vehicles, bridges, etc.

Further the report also looked at the findings of various studies which are briefed below along with reference to the original study.

Findings from Earlier Studies

A NCHRP study "Road Markings for Machine Vision 20-102 (6)" (*283*), has conducted an extensive closed environment testing on pavement markings. It has tested the visibility of pavement markings under eight different scenarios 1) daytime dry 2) nighttime dry 3) nighttime dry with glare 4) daytime wet 5) nighttime wet 6) nighttime wet with glare 7) nighttime dry with overhead lighting, and 8) nighttime wet with overhead lighting. Findings reported in the study were dependent on various factors such as luminance (CIE Y), retroreflected luminance (R_l), luminance coefficient under diffuse illumination (Q_d). The definitions of this terminology can be found in the report (*283*). Daytime visibility of markings was reported as a measure of luminance (CIE Y), luminance coefficient under diffuse illumination (Q_d) and MV system geometry luminance (L_v). Similarly nighttime visibility was dependent on the retroreflected luminance (R_l) and MV system geometry luminance (L_v). Further, the findings were reported in terms of detection confidence rating on a scale of 0 – 3, with 3 indicating the highest confidence. A value of 2 or higher is required for detecting the position of the vehicle within lanes, the type of lanes. Below list provides a summary of the provided recommendations:

- During daytime testing under dry conditions, a value of luminance (Y) greater than 23 yielded an average confidence rating greater than 2.
- Not many inferences could be obtained under wet time conditions during the day, likely due to limitations caused due to testing environment.
- During the nighttime testing under dry environments, retro-reflectivity value greater than 34 mcd/m^2 /lux had an adequate confidence level above 2.
- During the nighttime testing under a wet environment, retro-reflectivity value greater than 4 mcd/m^2 /lux had an adequate confidence level above 2.
- Daytime visibility was found to be negatively proportional to the operating speed, however, nighttime visibility was found to be non-influential of speed.
- Further research was required on evaluating the effects of cloud cover on machine vision. Similarly, concrete evidence was not obtained while evaluating the contrast markings.

In addition, the report highlighted the importance of various factors that are not characteristic of markings such as glare from the sun, glare from oncoming vehicles, weather conditions, shadows, etc. that are highly location specific.

Findings from FHWA Report

A FHWA report (*276*) claimed that for the technologies that enable vehicles to stay in their lane such as lane keep assist, three key elements need to be achieved with respect to pavement marking that are discussed below:

1. Uniformity

The report highlighted that having lack of uniformity in pavement markings within the US can be a huge cause of concern for AVs. Further, it also discussed that flexibility within Manual on Uniform Traffic Control Devices (MUTCD) allows for variability across the United States. Also, some concerns expressed by the AV industry such as insufficient contrast of markings were not addressed in the MUTCD. Figure 69 shows the states that are moving towards the 5-inch-wide and 6-inch-wide longitudinal marking as of 2019.

2. Design

Most of the observations pertaining to design are similar to the findings that are documented earlier in the report “Road Markings for Machine Vision 20-102 (6)” (*283*).

3. Maintenance

Maintaining the pavement markings to meet the standards that AV considers reliable is of utmost priority. According to this report, FHWA is on the path towards identifying the minimum retroreflective levels of pavement markings for human drivers. Similar kind of standards needs to be established for lane departure system/lane keep assist systems that need to be maintained for efficient AV operations.

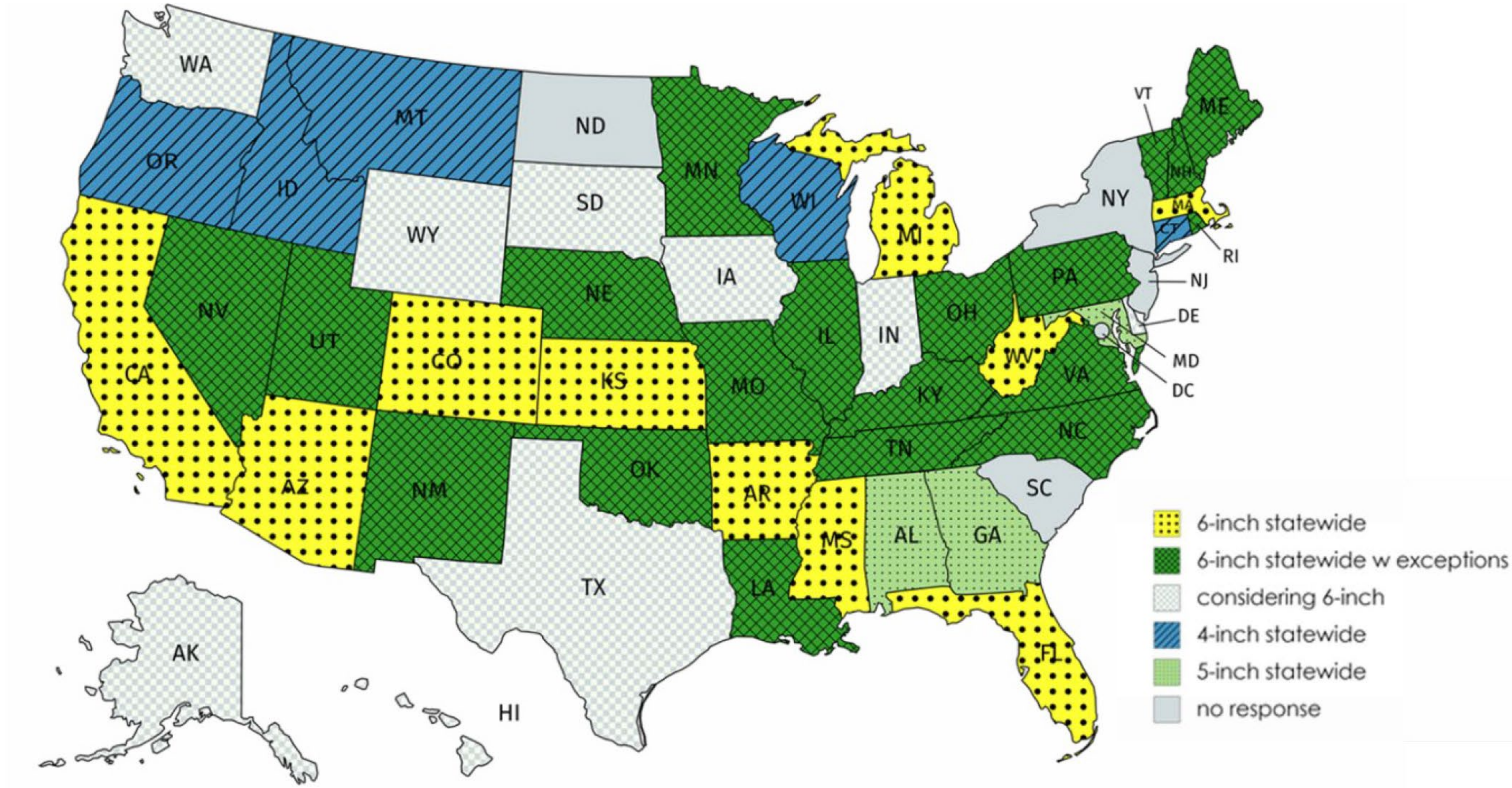


Figure 69 Width of pavement marking across the states. Source: FHWA

Findings from “Roads that Cars Can Read, EuroRAP”

A report from EuroRAP (*284*) on pavement markings recommends following guidelines for AV operations.

- Proposed to have a standard width for edge and lane markings i.e., 150 mm (~ 6 inch wide).
- Further, the reflectivity shall be at least 150 mcd/lux/m² and 35 mcd/lux/m² under dry and wet conditions, respectively.
- Considering retroreflective markings with sufficient visibility in all weather conditions is suggested.
- The edge of the roadways shall be defined with a continuous longitudinal solid line.

Maintenance of these markings shall be prioritized.

National Committee on Uniform Traffic Control Devices (NCUTCD) Recommendations

In response to FHWA’s request for information on the integration of ADS, NCUTCD has the following recommendations concerning pavement markings (*285*).

- Normal longitudinal line shall be 6 inch wide for interstates, expressways, and corresponding ramp interchange markings. Similarly for all other roadways that have posted speed limit greater than 55 mph and ADT > 6000 vehicles per day the normal line width should be 6 inch wide. For all other cases, the width can be 4 to 6 inches wide.
- Wide longitudinal lines must be at least 8 inch wide when used in conjunction with 4 inches normal lines and 10 inches wide when used along 6-inch normal line.
- Broken longitudinal lines on interstates, freeways, and expressways shall be 15-foot line segments with 25-foot gaps.

Traffic Sign Recognition System (TSRS)

TSRS is a system that endeavors to help drivers by providing the necessary platform to recognize the various road signs via the instrument panel, multimedia, or heads-up display. In the United States, various signs such as speed limit, stop sign, yield sign, and do not enter sign can be recognized by TSRS (*286*). The primary aim of TSRS is to provide information to the driver and help them make better safety decisions.

TSRS works on a relatively simple principle that reduces the hassle for road users. Front-facing cameras that are usually mounted near the rear-view mirror detect the road signs and the software processes, classifies, and relays the information to the driver, nearly in real-time. When a driver, for example, does not observe the posted speed limit or enters a "do not enter" roadway, some vehicles have a haptic (vibration) or audio warning that goes off. After displaying a recognized sign, the system may save it to the "memory" so that it can be recognized effortlessly the next time. Some systems use dedicated cameras solely for this system, while others use the same Advanced Driver Assist System (ADAS) camera that is being used for tracking the lane markings and proving lane departure warnings (*287*).

Challenges in TSRS from Earlier Studies

1. Anomalies

- Obscured signage: Vehicles, trees, roadside barriers, people, etc. may block the field of view of the sensors of an AV. This will limit the ability of the TSRS to identify the traffic signs (Figure 70(a)).
- Poor visibility, clarity, and recognizability due to adverse weather conditions (Figure 70(b)).
- Discoloration: As a result of long exposure to sunlight and the reaction of air and paint, the color of the signs starts fading (Figure 70(c)).
- Various lighting conditions: The lighting during day and night will be different (Figure 70(d)). This will cause a problem for TSRS (*288*).
- Resolution and illumination: The quality of an image can significantly degrade due to low resolution, and over or under illumination.

Figure 70 Challenges facing RSRS. Source: Lahmyed et al. (*288*)

2. System Accuracy and Efficiency: False positive and false negative are major issues for TSRS. It occurs when a TSRS wrongly classifies an object within its range of interest. For example, a false positive may occur if the camera of a vehicle detects and follows a speed limit sign that is a sticker on the back of its leader vehicle. This may lead to the AV taking risky actions and potentially causing a collision (*289*). Moreover, the limited memory and processing capabilities of the TSRS are also major challenges.

3. Lack of Standard Evaluation Benchmark: There is a lack of standard benchmarks for evaluating the accuracy of TSRS. The majority of the tests are done using a different dataset of traffic sign images. Some datasets may not contain all the scenarios (e.g.: fog, rainfall, night, day, etc.) and even if they contain all the scenarios, the extent to which the scenarios should be tested (e.g.: light rainfall, moderate rainfall, and heavy rainfall) might be lacking. Moreover, a system that is being evaluated might have homogeneous training and testing datasets. This will biasedly skew the accuracy rate upwards.

With a view to expand on the above-discussed challenges, the AV community was asked for their useful ideas regarding existing issues of the TSRS and ways to solve them, which are given below.

Current Challenges in TSRS:

- Lack of uniformity: There is a national standard, MUTCD. However, each state can also have its own standard if it is substantially similar to the MUTCD (*290*). For Texas, it is TMUTCD. So, if an AV is driving from one state to the other, it might pose a challenge even due to the slight variabilities among traffic signs used.
- Lack of maintenance: Poor maintenance of traffic signs will cause the text and/or color to deteriorate.
- False-negative and false-positive: False information perceived by the sensor might lead to detrimental consequences.
- Vandalism: It is a serious concern since it can cause detrimental driving behaviors. Moreover, the vandalized signs need to be repaired or replaced which increases the cost to transportation agencies.
- Occlusion: Occlusion of traffic signs might occur due to several reasons, such as vegetation, high profile vehicle in the line of sight of the vehicle, parked vehicle near an intersection, placement of signs, etc.
- Illumination: Too much reflectivity can blind the machine vision. Additionally, the flicker/refresh rate of electronic signs used can cause a problem if not standardized.
- Railroad crossing: Railroad crossing is a major concern for AVs due to its limited line of sight and inability to hear the horn of train.
- Lack of training data: The sensors on an AV perceive the traffic signs and matches them with its database. If the captured image is not in its database, then it will pose a problem.

Solutions as per AV Experts:

- Delivering up to date digitized signs and well-maintained traffic signs.
- Training AVs to overcome variable traffic sign infrastructures (For e.g., not all STOP signs are the exact same. They might have variance in terms of height, color, etc.).
- Providing V2I, V2X communication might help.
- Ensuring proper placement of traffic signs is critical.
- Having retroreflective coating, RFID tags, or paint on the traffic signs.

A couple of follow-up questions were asked regarding traffic signs (traffic sign on either side of roadway and illuminated traffic signs). The response from the AV community is listed below.

Traffic Sign on Either Side of Roadway: Providing traffic signs on either side of the roadway might help in various conditions. It can overcome the problems caused by occlusion. Some experts agree that providing signs on either side is beneficial (as long as they are uniform) for AVs that rely heavily on machine vision. If a two-lane highway has a high freight movement thereby restricting the field of view of smaller AVs, having signs on either side is beneficial. This might not entirely hold true for multilane highways as smaller AVs can be sandwiched between two heavy vehicles driving in parallel lanes. While other experts believe that there are already too many distractions for a human driver on the road (traffic signs and advertisements). Providing additional signs will only make it worse for human drivers. Hence, no unanimity has been reached among the AV experts regarding having traffic signs on either side of a roadway.

Illuminated Traffic Signs: Providing illuminated traffic signs and maintaining them is troublesome and expensive work for traffic agencies. The illumination causes inconsistency (flicker/refresh rate and glare) in the way they function and are counterproductive in comparison to retroreflective signs. Moreover, they might cause distractions to some human drivers. However, this conclusion needs to be supported by a survey from the human drivers.

Classification of Roadways

IOOs oversee the transportation network and infrastructure. The current roadway system is designed as per human driver's capabilities. Horizontal curve on the roadway depends on the lateral acceleration of the human driver while the vertical curve depends on the SSD. SSD in turn depends on the ability of the driver (perception and reaction time) to react to obstacles on the road. The fonts, colors, and materials used in the various traffic signs and symbols are based on the driver's visual ability to perceive information. With the arrival of AVs, there has been a renewed focus on how highways should be planned, developed, operated, and maintained to maximize safety and mobility. The technologies and sensors used in AVs have the potential to detect and perceive the roadway environment in order to assist drivers to perform the driving tasks or perform the driving tasks themselves. For a reliable and effective vehicle operation, the information on what sort of infrastructure is needed to support the deployment of AVs is vital to IOOs. A classified roadway system might come in handy in this case (*291*).

IOOs, as well as the automotive industry, might benefit if a roadway classification system is created. The finding of the NCHRP 20-24(112) report is a Connected Roadway Classification System (CRCS) that can benefit IOOs, DOTs, and MPOs. CRCS will help in planning and implementing AV/CAV compatible infrastructure. The report focuses on three distinct infrastructure approaches (talking to the road, seeing the road, and simplifying the road) and four different classification levels as shown in Figure 71 below.

Infrastructure Approach	What It Is	CRCS Levels			
		Needs Upgrade & Maintenance	**Meets Current Best Practices**	**Meets Emerging Market (1–5 years)**	**Meets Next Decade Market (10 years)**
Talking	Electronic communications between vehicles & roadway	• Limited or no fiber installed • Limited or no cellular coverage • Limited or no roadside devices with communication • Signal equipment outdated with no connections • Temporary TCD deployed with no communication	• Fiber along roadway with access points • Good cellular coverage • Updated signal controller, meets MUTCD, connected as part of system • Infrastructure has no V2I capability • TCDs connected	• DSRC or C-V2X nodes tied into fiber • Signal is equipped with V2I communication capability • Infrastructure has V2I capability • TCDs able to connect to cellular or fiber	• Small cells deployed along roadway with 5G coverage • Signal transmits SPaT messages • Infrastructure transmits information on conditions with local processing capability
Seeing	Infrastructure (e.g., signs & markings) readable by vehicle sensors	• Roadway assets are not in digital form • Signs and markings are either not present and/or fall short of MUTCD retroreflectivity guidance • Signals in need of upgrade	• Digital inventory of roadway assets exists • Signs and markings are present and meet MUTCD retroreflectivity guidance • Traffic signal equipment meets MUTCD	• Major corridors or areas have digital maps • Signs and markings meet revised MUTCD CAV visibility guidance • Signals are consistent, visible, and use glare reduction backplates	• Signs and markings include technology that provides for future machine visibility and processing • Research is needed on how AVs see signals
Simplifying	Design & operations for AV vehicles & their uses	• Infrastructure geometry, temporary TCDs, and permanent TCDs may not meet AASHTO or MUTCD guidelines • Pavement in poor condition	• Infrastructure geometry meets AASHTO design guidance • Pavement free of defects • Temporary and permanent TCDs meet MUTCD guidance	• Infrastructure geometry is designed to facilitate navigation by CVs/AVs • Navigational aids are V2I capable • Research is needed	• Infrastructure geometry and navigational aids are specifically designed for CVs/AVs only • Research is needed

Figure 71 Overview of CRCS framework. Source: NCHRP (*291*)

Need for a classification system

- To inform drivers and passengers about their responsibilities on the roadways, removing any imprecision during the driving task assignment.
- Can act as a framework for discussion among automotive and infrastructure industries.
- Can help in better and planned infrastructure investment.

CDOT classification of roadways (*276*):

CDOT proposed a six-level roadway classification system based on the roadway's ability to support operations, ITS, AVs, and CVs. Each of the levels is briefly discussed below:

- Level 1: Unpaved and/or un-stripped roads.
- Level 2: Paved roads meeting AASHTO standards and pavement markings as per MUTCD guidelines. Absence of ITS equipment or infrastructure to collect vehicular data.
- Level 3: Presence of ITS equipment and one-way data sharing between DOT/vehicle/user and/or mixed-use lanes.
- Level 4: Two-way data share between DOT/vehicle/user and/or lanes designated explicitly for level 3 and level 4 vehicles. Presence of adaptive ITS equipment (smart signals, automatic highway lighting, etc.) on a roadway or specific lane(s).
- Level 5: Also known as advance guideway system. Roadway or specific lane(s) designed explicitly for level 4 vehicles. Presence of additional features, such as inductive charging, and advanced data sharing. No need for roadside signs as all the information is depicted directly to the onboard system of a vehicle.
- Level 6: All the lanes of a roadway are designed for a level 4 vehicle. No need for signs, signals, and pavement markings.

The AV community provided valuable insights regarding a classified roadway system based on the AV readiness index that are listed below:

- Beneficial for IOOs, developers, and DOTs.
- Collaboration and data sharing between OEMs and IOOs to reliably determine if AVs are in their ODD.
- Suitable only if there is consensus among various involved parties (IOOs, developers, and industry).
- Should be made uniform throughout the nation.
- The classification should be based on thoroughly investigated parameters.
- Might help but the vastness of the road network will pose a serious concern.
- AV developers are already using their own road classification implicitly.
- Rather than classifying roads, develop a composite matrix that compares the quality or readiness index of roadway infrastructures, such as quality of markings, digital communication, etc.
- Not a feasible operational solution for the next 20 years.
- Liability and insurance issues.
- May cause alarming concerns in mixed traffic.
- A futuristic approach.
- At present, can be only done for the lower level of autonomy (level 2).

- Limited amount of money available to upgrade roadway infrastructure. Hence, the focus should be to develop AI and intelligent sensors into vehicles themselves rather than on roads.

The responses of the experts regarding having a classified roadway system based on the AV readiness index are tabulated below as shown in Table 49.

Table 49 Opinion on classified roadway system

S.N.	Category	Number of responses
1	Beneficial	7
2	Maybe beneficial	8
3	Not beneficial	8
4	Not sure	5

Digital Maps

A high-definition map sometimes referred to as a 3D map is often considered a digital twinning of road networks with all the properties of the infrastructure inbuilt into the system. It is said to have properties such as traffic signages, location of bike lanes/ bus lanes, pedestrian crossings, lane widths, number of lanes, ramp details, etc. Overall, it is said to have information about the complete infrastructure system and forms a fundamental functionality of an ADS and sometimes for ADAS. Considering the importance associated with such a system, a group of questions was asked to the AV community regarding their effectiveness. Based on the open-ended responses from participants it has been categorized as highly advantageous to have, somewhat advantageous to have, not so advantageous to have, and not sure. Table 50 represents the distribution of responses.

Table 50 Priority of Digital Maps

S. No	Category	Number of responses
1	Highly advantageous	23
2	Somewhat advantageous	1
3	Not so advantageous	1
4	Not sure	3

As observed in Table 50, a digital map was perceived as one of the most requisite for an AV to operate on the roads since it provides accurate information about the geometric elements along with lane markers. Therefore, it is commonly used in the localization of the vehicle i.e., to position the vehicle inside the lane. A commonly known challenge with digital maps is the inability of the maps to provide information such as debris on the pavement, tire burst remains, etc. therefore a follow-up question was asked on the importance of having machine vision into the system. A commonly accepted belief is that current technology still relies on machine vision to make decisions in real-time which cannot be achieved by complete digitization, therefore at least for the near future machine vision is still going to be a predominant characteristic that AV must possess especially in the ADAS systems. Therefore, a common consensus is that machine vision supplemented by digitized maps is the direction of current technology at least for the short-term future.

Some selected transcribed responses on the importance of digital maps:

- In favor of the digital maps but cannot be the only source of information.
- Absolutely important, solves problems associated with perception sensors, especially under unfavorable weather conditions.
- Might help but not needed necessarily.
- It solves the problem of having illuminated traffic signs if having them is a proposed solution. Supplying power to illuminated traffic signs is a big concern that becomes further challenging in rural environments.
- Having an HD map will help the AV but essentially AV should have more than one form of information to make a decision.
- Machine vision and HD maps have their own advantages, to obtain optimal benefits AV shall require both.
- Both are needed with HD maps outweighing machine vision marginally in the early stages, however, if the machine vision technology progresses and can detect the surroundings under challenging conditions then machine vision may prove sufficient.

Advantages of having digital maps:

- Highly efficient and accurate in providing the infrastructure system to vehicles.
- Extremely useful to provide information on static infrastructural elements such as the location of ramps, bridges, traffic signals, signages.
- Beneficial in providing information to vehicles under adverse weather conditions such as snow, fog, rains, etc.
- Advantageous in regions with dense traffic sign systems such as on urban roads that could be challenging for machine vision.

Challenges of digital maps:

- Digital maps currently are static, and they do not have the provision to be real-time.
- Information from digital maps needs to be backed up with machine vision or vice versa.
- Does not capture traffic disruptions, traffic incidents, redirection of traffic, work zones, etc. automatically.
- Expensive to develop digitized maps for huge regions and maintain periodically.

Urban Condition

The urban road networks can present another class of challenges for AV machine vision and decision-making. Similar to freeways, challenges for urban roads were identified from the earlier studies and disengagement report (*278*). AVs were found to have troubles in certain configurations such as signal-controlled intersections and stop-controlled intersections. In addition, another observed challenge from literature is to perform left turns especially uncontrolled left turns, and maneuver over segments with lane reductions. A brief summary of reported disengagements (*278*) relevant to infrastructure are summarized in Table 51.

Table 51 Selected summary of disengagements relevant to infrastructure

Description of disengagements	Type	Number
The operator disengaged the system manually to remain in the operational design domain. This was accomplished by pressing the brake pedal to reduce the velocity of the vehicle.	Any	389
Safety Driver disengaged to ensure proper behavior at traffic light.	Urban	184
Safety Driver disengaged near crosswalk due to overly conservative vehicle behavior.	Urban	131
Safety Driver disengaged upon judging that vehicle was too close to road boundary.	Urban	62
During a merge, the test vehicle failed to keep an appropriate distance between a merging car, or the merging car failed to yield to us. Conditions: Non-inclement weather, dry roads, no other factors involved	Freeways	56
Safety Driver disengaged to manually drive through crosswalk.	Urban	43
Safety Driver disengaged due to cut-in issue.	Freeways	26
AV turning right. Construction warning signs on the side of the turn not detected by AV. Driver takes over to avoid AV getting close to the construction zone.	Work zones	24
The software detected an inanimate object in the AV's path and triggered an Estop	Any	18
Delivery truck parked in lane, would break rules to cross into oncoming lane to get around it	Urban	13
During an exit/merge the test vehicle was going the "correct" speed as posted by road signs but was going too slow or too fast given the traffic and road conditions. Conditions: Non-inclement weather, dry roads, no other factors involved	Freeways	13
AV making wide right turn, with oncoming vehicle in opposite lane of a narrow street. Driver makes a preventive intervention to avoid any unsafe situation. Cause: Lateral controls issue causing wider than usual turn.	Urban	11
Driver makes a preventive intervention, when he sees an on-coming vehicle on a narrow street with parked cars on either side leaving narrow gap for both vehicles to pass each other.	Urban	8
Localization Issue: Failed to stop within a certain distance of stop line at traffic light	Urban	5
This occurs when the test vehicle is making an autonomous lane change and it cuts across the lane marker into another lane. Conditions: Non-inclement weather, dry roads, no other factors involved	Freeways	5

Note: Only disengagements that are greater than or equal in value of 5 have been reported here

Source: Disengagements report (*278*)

As observed in table 51, few of the disengagements were preventive in nature and have been performed as a precautionary measure. The below section provides a summary of findings for urban infrastructure.

Lane Reductions

Reduction in lanes is observed commonly in our current roads therefore it was enquired whether the reduction in lanes could be a challenge for AVs as given in Figure 72.

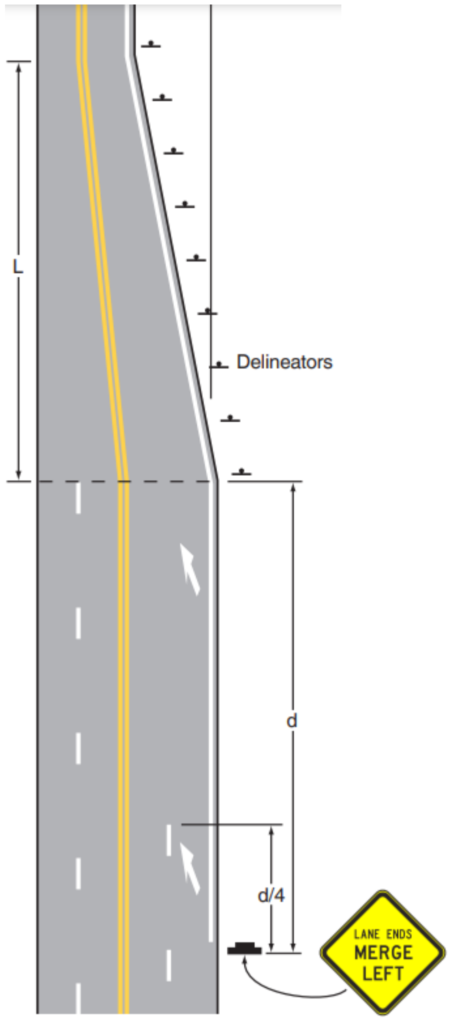


Figure 72 Lane reduction with transitional pavement markings

Source: TMUTCD

Below are some transcripts of opinions expressed by the experts:

- Having a well-defined HD map should provide such information therefore AV can take an informed decision.
- With HD maps AV can stay in the left-most lane therefore it does not pose a concern.
- This is not as concerning as a merge operation but can still be a challenge under certain circumstances.

Intuitively, the suggestion that performing a change of lane by using an HD map well before reaching this point is not a sustainable option, since it could underutilize the existing infrastructure system. Eventually AVs have to be trained to perform such a merging maneuver. Therefore, a follow-up question was framed on evaluating the criticality of “lane drop signage” and “transitional pavement marking.” Below are the findings from the expert opinions:

- Transitional pavement markings are critical in this maneuver.

- Pavement markings supplemented by appropriate signages should solve the above challenge.
- Traffic signages with supplemental plaque mentioning the distance of such point can benefit the AVs.
- Overall, for transitional pavement markings on a scale of 1 to 5 (with 5 being the highest priority) an average of 3.8 value has been recorded.

Protected Left Turns

Experts were asked for opinions on having dotted lane line extensions through the intersections as shown in Figure 10. Most of the experts agreed that AVs that rely on digital maps shall not necessarily need pavement markings to make such maneuvers, however many identified that it is important for the AVs that rely on machine vision in decision making. Hence, as understood at this stage the current technology still requires both HD map and machine vision in decision making, therefore having the dotted lane line extensions shall be recommended. Further many of the experts harmonized that the lane markers are more critical to human drivers than AVs in assisting to stay within the lane. Achieving conformity of human drivers to stay within their lane is extremely crucial because AVs follow a standard path and would obey the defined rules, therefore non-conformity of human drivers can sometimes lead to vehicles getting stranded in the middle of an intersection. Overall, it is recommended that signalized intersections shall have dotted lane line extensions, especially in the intersections that have more than one turning lane as shown in Figure 73. Further it is also recommended to have dotted lines that lead to the left turn lanes to have efficient operation.

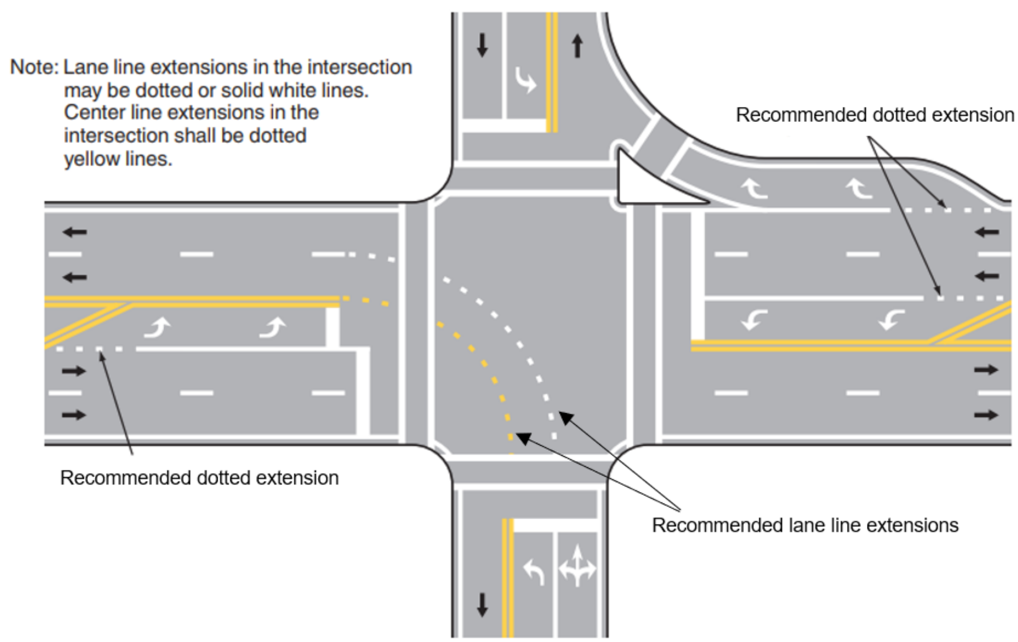


Figure 73 Layout of a typical intersection with left turning lane line extensions and dotted extensions

Source: TMUTCD

Unprotected Left Turns

Under unprotected left turns, vehicles need to yield to oncoming vehicular traffic and then turn. Experts opined under such situations that it's the ability of the sensors and radars that have to improve and AVs shall be trained for all possible scenarios to accept different types of available gaps. This can be achieved as the technology continues to progress and evolve. Further, having connectivity among vehicles and infrastructure can improve the performance of AVs under such scenarios.

Stop Controlled Junctions

Another aspect that has been discussed in the disengagements report (*278*) is that the performance of AVs at stop-controlled junctions is too conservative and the safety driver is forced to take control of the vehicle. This is particularly evident at T- junctions where cross traffic does not stop. Some of the findings related to this aspect are as follows:

- The ability of the sensor has to improve in detecting the oncoming vehicles especially, to maneuver at T-junctions.
- Vehicles must have a clear line of sight from stop lines, unlike human drivers AVs do not cross the stop line to get a better view of cross traffic.
- Supplemental plaques as shown in Figure 74 are important, especially for T junctions.
- The range of sensors/radars perpendicular to vehicles length is usually limited therefore T junctions can be a challenging maneuver, hence the range of sensors/radars must improve.

Figure 74 Stop controlled sign with supplemental plaque. Source: TMUTCD

When further asked if having an additional sensor at T-junctions that could relay the information of gaps available, many experts disagreed with such thought, especially because:

- It is very costly to install and maintain at each stop-controlled intersection.
- Sensors cannot predict the variability in human driver’s behavior accurately.
- Could rise a concern of liability provided if an incident/crash occurs.

Further at all-way stop-controlled intersections, experts believed the performance of AVs have to improve and behave a little more aggressively, which is believed to be attained as technology advances. Also having visuals such as flashing waves, flashing lights, or aural message on the vehicle is believed to assist in conveying the information to other human drivers

Freeways Condition

After reviewing earlier studies and exploring the disengagement report (*278*), major points of concern for the freeways from the infrastructure standpoint are the following:

- Entrance ramps,
- Exit ramps,
- Lane drops without proper markings, and
- Merge operations.

Table 52 summarizes the list of licensed AV companies that are allowed to assess along with a summary of disengagements based on facility type.

It should be noted that not every company might assess all functional classes of roads. Therefore, careful consideration must be given while making suitable inferences. However, it cannot be denied that there are plenty of interferences on urban roads and disengagements are expected to be high. On the other hand, the number of disengagements on freeways was relatively small (approximately 8 percent). When investigated further majority of the causes of disengagement were as listed initially especially at ramps. Few other causes of disengagement such as inappropriate change of lanes, inappropriate trajectories, etc. were assumed to be company-specific that can be solved with further testing.

Table 52 Summary of disengagements for different functional class of roads and parking facilities

Organization name	Freeway	Highway	Parking facility	Street	Grand Total
AImotive Inc.	113				113
Apple Inc.	2	3		125	130
Aurora Innovation, Inc.	1	1		35	37
AutoX Technologies, Inc				2	2
BMW of North America				3	3
CRUISE LLC				27	27
DiDi Research America LLC				2	2
EasyMile				128	128
Gatik AI Inc.				11	11
Lyft				123	123
Mercedes Benz Research & Development North America, Inc	45			1122	1167
Nissan North America, INC				4	4
Nuro, Inc				11	11
NVIDIA	75	18		32	125
PONY.AI, INC.				21	21
QUALCOMM TECHNOLOGIES, INC.	64	26			90
Ridecell Inc				189	189
SF Motors, Inc.		36		25	61
Telenav, Inc.			2		2
Toyota Research Institute				1215	1215
Udelv, Inc				49	49
Valeo North America Inc.				99	99
Waymo LLC		4		17	21
WeRide Corp		2			2
Zoox, Inc				63	63
Grand Total	300	90	2	3303	3695

Source: Disengagements report (*278*)

Two identified challenges for ADS and ADAS at on and off-ramps are:

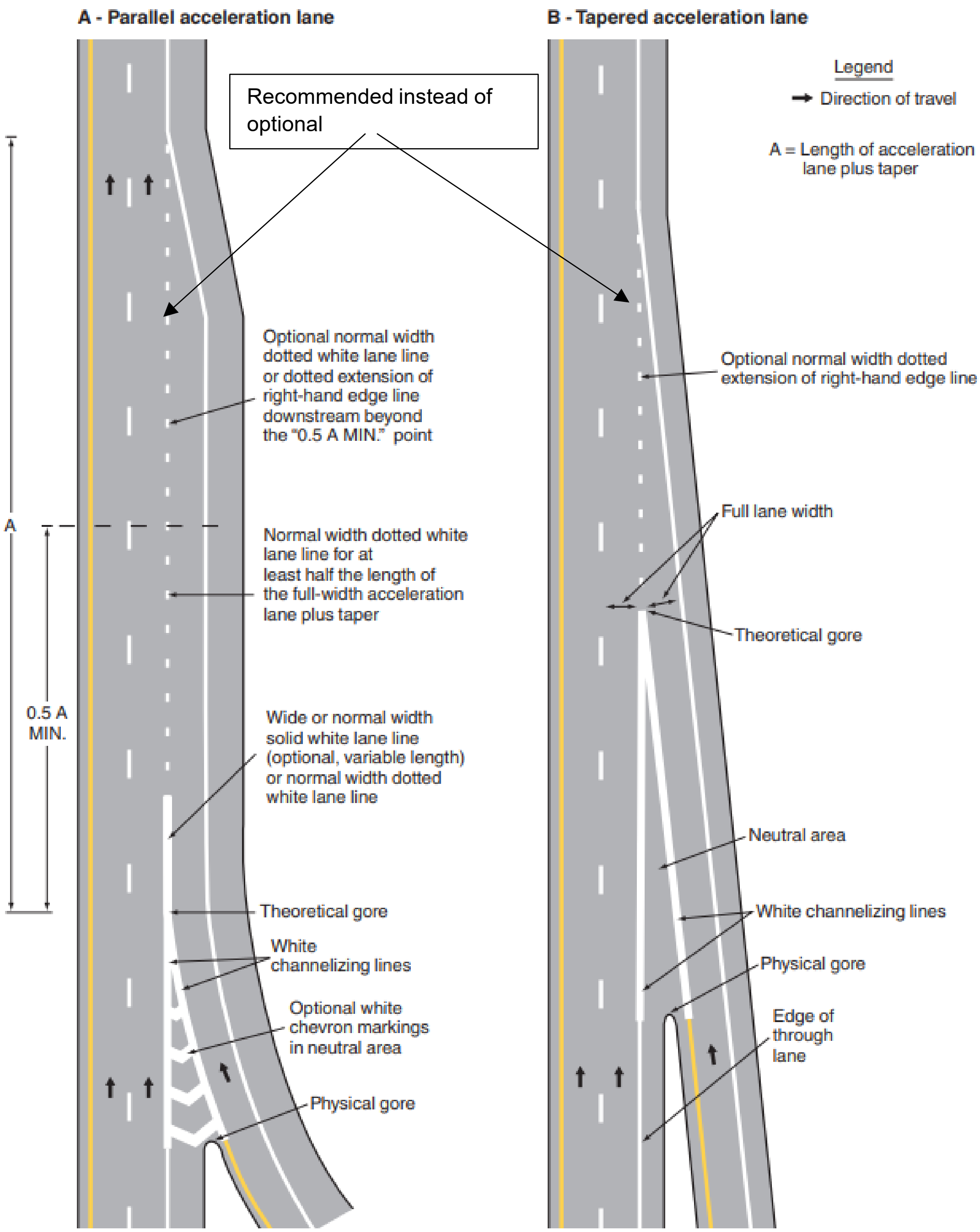
- Gap Acceptance, and
- Localization.

Following sections provide a brief explanation of these challenges and identified solutions.

Entrance Ramps

It is understood that the current technology of AVs is programmed to be conservative and the behavior of human drivers at merge points, especially at entrance ramps, is highly location specific and usually is extremely aggressive that makes it even more challenging for AVs to operate on such locations. Owing to this conservative behavior, gap acceptance of AVs can be poor which could result in the stranding of vehicles. Most of the interviewed experts agreed that the behavior of AVs needs to improve to oversee this kind of maneuver which is possible as the technology advances. In addition, it was suggested that having V2V and V2I connectivity could alleviate this problem. In line with the above discussion, experts were presented with different layouts of acceleration lanes from Texas MUTCD (*292*) at entrance ramps and were asked for suggestions of improvement to improve AV performance.

As discussed in digital map sections earlier, AV operates based on HD maps and machine vision, further, it was agreed by the experts that machine vision requires the dotted line-markings to locate itself within the lane (as observed in Figure 75), often known as “localization”, therefore in the event of reliance on machine vision absence of dotted line markings can be alarming for AV maneuver. Further few of the experts identified that among different available taper lanes “parallel acceleration lanes” seem to be the most preferable option since it allows for clear demarcation of lanes. The least preferred option was “tapered acceleration lanes” with white channelizing lines that are not extended until the theoretical gore as shown in Figure 75 (c). Under such circumstances, AV relying on machine vision could be confused in locating itself. Therefore, in the case of tapered lanes, having channelizing lines until the theoretical gore and extending the dotted lines is a suitable alternative. Similar findings were observed in the FHWA study (*276*).


A - Parallel acceleration lane
B - Tapered acceleration lane
Recommended instead of optional
Legend
Direction of travel
A = Length of acceleration lane plus taper
Optional normal width dotted white lane line or dotted extension of right-hand edge line downstream beyond the "0.5 A MIN." point
A
Normal width dotted white lane line for at least half the length of the full-width acceleration lane plus taper
0.5 A MIN.
Wide or normal width solid white lane line (optional, variable length) or normal width dotted white lane line
Theoretical gore
White channelizing lines
Optional white chevron markings in neutral area
Physical gore
Optional normal width dotted extension of right-hand edge line
Full lane width
Theoretical gore
Neutral area
White channelizing lines
Physical gore
Edge of through lane

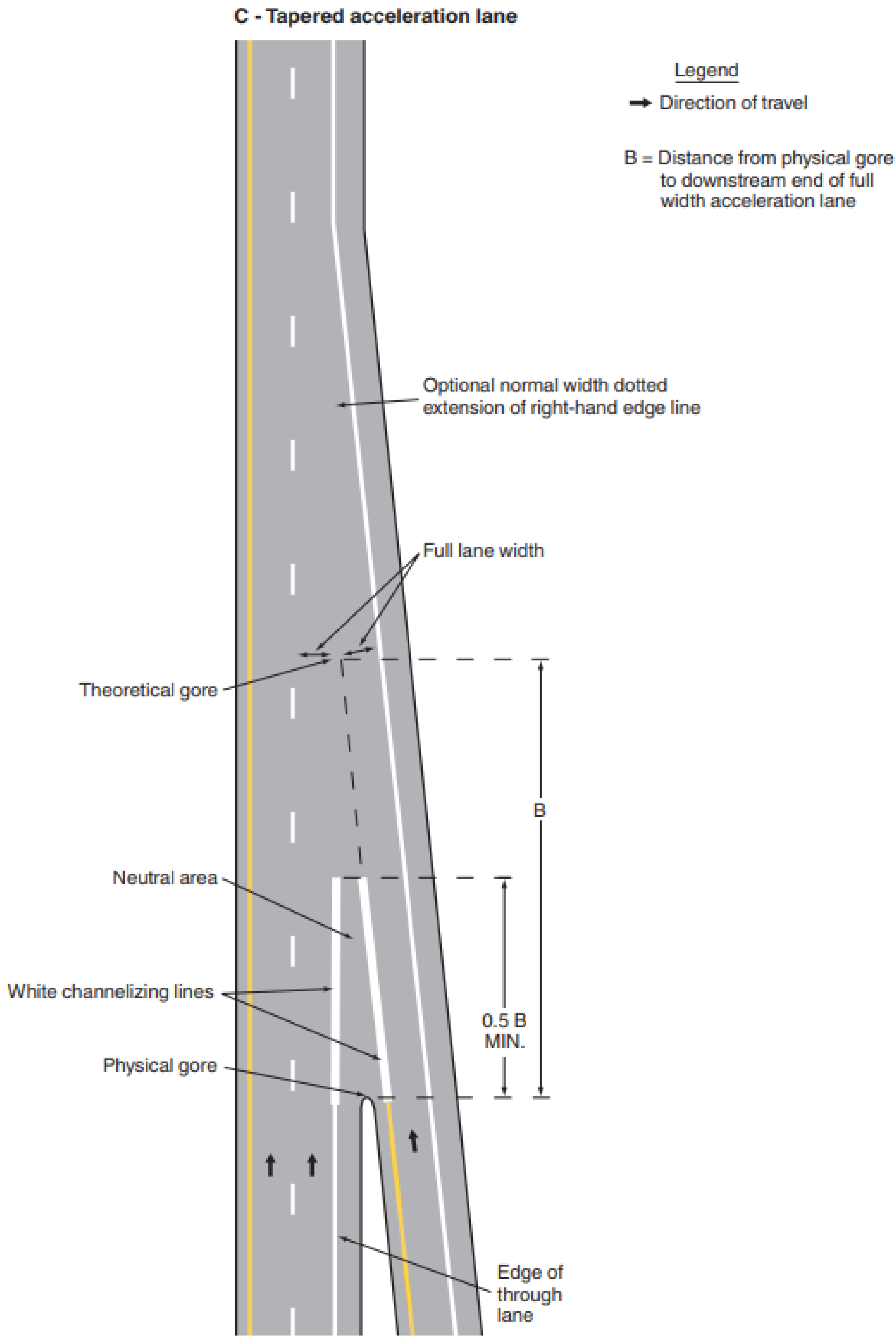
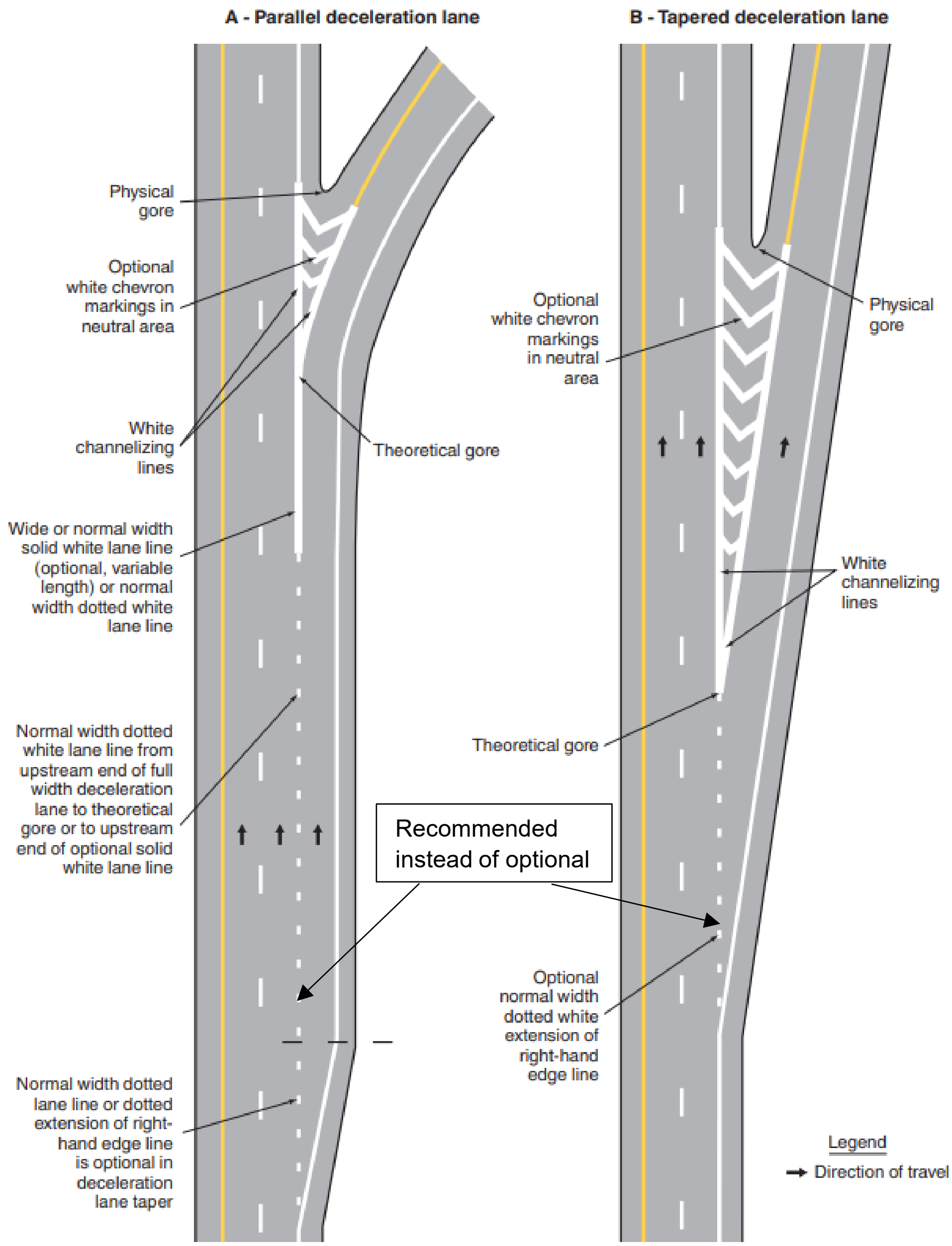


Figure 75 Depicting various alternatives of acceleration lanes a) parallel acceleration b) Tapered acceleration and c) Tapered acceleration with minimum channelizing lines

Source: TMUTCD

Exit Ramps

Similar to entrance ramps, opinions on having dotted line markings on exit ramps were explored. Many of the experts resonated with the opinion that having dotted line markings is extremely beneficial for AV maneuver while few of them went further and said having dotted line markings is more critical at exit ramps in comparison to entrance ramps because vehicles exiting a freeway travel at high speeds and must make decisions swiftly. Any ambiguity at such speeds might be detrimental. Current TMUTCD specified that dotted line extensions to be optional however for ADS it appears that these dotted line extensions as shown in Figure 76 should be mandatory. Therefore, as suggested in reports (*276*, *293*) it is highly recommended to maintain the dotted line-markings at the exit ramps. In addition, having V2V and V2I connectivity at off-ramps could solve the problem of gap acceptance of AVs.



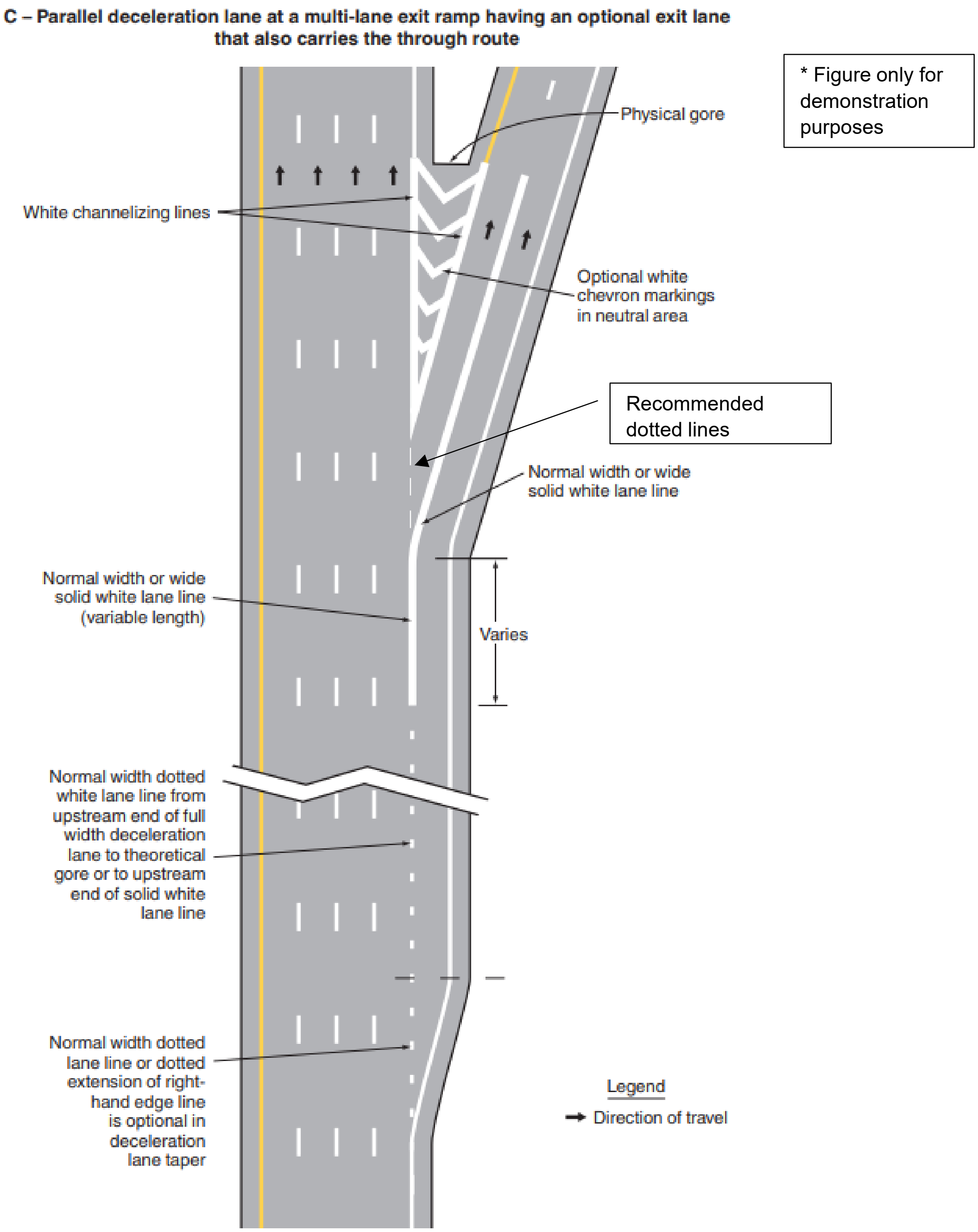


Figure 76 Different layouts and exit ramps a) parallel deceleration b) Tapered deceleration and c) parallel deceleration at multi-lane exit ramp. Source: TMUTCD

Practice of Draping Cloth on Traffic Signages

Another aspect that has been explored is the current practice of draping signage with black material if it is no longer needed or when a substitution is to be made. Many of the experts believed that this practice is not going to be a challenge provided relevant signages on updated information are provided (if needed). This is because the AV industry trains the algorithm based on the database of images and ideally this practice is also accounted for. Therefore, the practice of covering signs with black material can still be followed.

Gore Area

Findings from earlier studies suggest that uniformity of markings along gore areas is essential. However, the report (*276*) further stated consensus among AV developers has not been reached yet. It is divided on whether gore needs to be painted with chevron markings or should be marked solid entirely.

Shoulder Width

A commonly known fact with AVs is that they are programmed to perform a minimum risk maneuver when disengaged preferably moving onto the shoulders. This maneuver could be challenging especially for freight organizations since not all segments of the road network can have enough shoulder width. Further, it is not feasible to increase the width of shoulders considering the limited availability of roadway width and land acquisition cost. Nevertheless, increasing shoulder width has been shown to improve safety (*294*). When enquired about such a challenge few of the experts mentioned that providing detailed information on the availability of shoulder widths to the AV industry could enable efficient planning of their operations and plan for unprecedented events. Not to mention such a challenge can also be solved by maintaining up-to-date digital maps.

Work Zones

The dynamic nature of a work zone poses a challenge for both AVs and human drivers. A work zone is a section of a road where highway construction, maintenance, or utility work is taking place. Temporary traffic control devices (TCDs), such as signs, channeling devices, barriers, pavement markings, and/or work vehicles, are commonly used to identify a work zone (*295*). TCDs allow for safe and simple deployment, as well as the flexibility to adapt to changing traffic patterns and quick removal after the task is completed (*276*). However, temporary TCDs are less uniform in comparison to permanent TCDs which can lead to disruption in the movement of AVs through a work zone.

Hence, in order to identify the challenges and possible solutions regarding work zone, AV experts were asked about their views regarding zipper merge, and the use of vertical delineating devices and orange pavement marking in work zones. Their responses are discussed below:

Zipper Merge: The majority of the experts believe that providing some sort of information (speed, direction, acceleration, deceleration, etc.) of the surrounding vehicles through connectivity will be beneficial in zipper merge areas. Increasing the sensors and aggressiveness of an AV might help in some conditions. Some of the major findings are:

I. V2V, V2I, and V2X communication: It can provide connectivity capabilities to both CAVs and HDVs and install an AI controller in the AV that will receive driving information including speed, direction, acceleration, and deceleration (through connectivity) of every vehicle in the traffic stream.
II. Providing real-time information through the work zone data exchange.
III. AVs are conservative with respect to clearance for merges and human drivers tend to leave minimal space in low speed/congested conditions. Transitional information supplied by signage, LED message boards, proper temporary

measures that include striping, and other acceptable merge markings can be beneficial.

IV. Following standards and working on algorithms that replicates human driver behavior.

V. Similar problem as sudden lane drop/increase.

VI. Decision making in AVs: Lane changing maneuvers is a complex task for AV near zipper merge. In a mixed traffic condition, the lane change by an AV depends on how fast the vehicles in the target lanes are driving and the gap they are maintaining. Increasing the sensors in AVs and their aggressiveness might help in such situations.

Vertical Delineating Devices and Orange Pavement markings: Vertical delineating devices, such as pylons, drums, cones, etc., and orange pavement markings (used in Europe and Canada) are used to separate the work zone from the roadway traffic. However, in some cases, the machine-vision system fails to detect them, especially at low visibility and adverse weather conditions. Experts provided their opinions on challenges and solutions associated with this issue and are listed below:

Challenges:

I. Variation: Displacement and/or improper positioning of vertical devices.
II. Colored pavement for work zones is likely unrealistic for agencies to implement.
III. Having orange colored marking over vertical delineating devices does not have any benefit unless the lane marker color was changed well upstream.
IV. Human drivers tend not to cross vertical delineators in a work zone. This might not hold true for orange markings.
V. Poor quality paints and heavy work zone vehicles that lay down dirt across the road can hamper the performance of AVs if they are dependent on pavement markings.

Solutions:

I. Uniformity in work zone devices used.
II. Work zone data exchange and ITS: USDOT's work zone data exchange provides information regarding work zone activities to help AVs and human drivers navigate through a work zone in a safe and efficient manner.
III. Radar reflective vests, sensors on work zone cones.
IV. Orange color can be easily detected by AVs. Further studies are required regarding orange pavement markings.
V. If ample number of staffs are present and the area is geofenced, keep the digitized map up to date with information regarding work zones.
VI. Taking an alternative route rather than navigating through work zone can be productive in some instances if an alternative route is available.

Traffic Signals

The traffic signal is a key part of the roadway-infrastructure element that ensures a smooth, safe, orderly, and efficient movement of vehicles through an intersection. It plays a vital role in supporting AV technologies because of its capability to communicate Signal Phasing and Timing

(SPaT) data to oncoming vehicles (*296*). SPaT gives the information of the current phase as well as the residual time of the current phase at a signalized intersection for every approach and movement (*297*).

However, there are numerous challenges that an AV faces while navigating a TLC intersection. AVs, unlike human-driven vehicles, rely exclusively on their computer vision system and the data provided to train them to drive around. Presently, even the best self-driving assistance system misperceives some things occasionally in their environment. Passengers, pedestrians, bikers, and others are all at risk if that misperceived object is a traffic signal and the car gets it incorrect (*298*).

The vision system and algorithms used to detect the traffic signals lack robustness and are depicted by the disengagement report (*299*) where the automated system transfers the control to a fallback-ready user to ensure proper behavior at traffic lights. Moreover, the non-conformity of human drivers is also a major challenge for AVs. AVs are programmed to be conservative due to safety reasons. This might not hold true regarding human drivers. Human drivers might take advantage of AVs and are often aggressive and tend to break rules (run a red light, do not yield at a yield sign, etc.).

On top of the above-mentioned issues, lack of consistency in the vertical and horizontal positioning of traffic signal heads and traffic signal relevance are some of the major challenges regarding the traffic signal system. The AV communities provided their valuable insights and recommendations which are summarized below:

- Traffic signal head consistency: The majority of the responders agree that having consistency in the horizontal and vertical alignment of traffic signal heads might help. However, it is not absolute necessity and is impractical. If an AV system uses an HD map to navigate, it should already contain the necessary information regarding the location of traffic signals ahead of time. On the other hand, if an AV system uses machine vision (sensors) to navigate, as long as the traffic signal heads are within its range, consistency is not deemed crucial. Moreover, the traffic signal heads are found in various versions and configurations which makes it even more difficult to achieve consistency. They also believe that CV technology with SPaT messaging is beneficial.
- Traffic signal relevance: One of the challenges of a big urban signalized intersection is to recognize the relevant traffic signal head of various lanes. The AV community indicated that having a dedicated signal head per lane will be helpful and HD maps can supplement it. In this regard as well, CV technology with SPaT/Map messaging is beneficial. This issue is not valid for every intersection. Hence, research needs to be done in finding critical locations for this issue and once found should be addressed.

Active Modes

The active mode of transportation is a sustainable and environment-friendly method of personal travel. The introduction of AVs has the potential to affect how people perceive active modes of travel. AVs as of today are operated in a constrained geofenced area. The presence of bicyclists and pedestrians in such areas can restrict the AVs even more in terms of functionality. The safety of road users (pedestrians and bicyclists) is of critical importance to the AV industry (OEMs, IOOs, DOTs, etc.). In a mixed traffic environment, the sensors of AVs find it difficult to detect and predict the movement of non-motorized road users (*300*). In order to ensure effective movements of AVs in the environment containing vehicle-human interactions, OEM driven approach (improvement to sensors, V2P interface, etc.) is not sufficient. Efforts from the IOOs should also be made in terms of providing sufficient, improved, and standardized multimodal infrastructures including bicyclists/pedestrians infrastructure, ADA-accessible infrastructure, parking, and more (*296*).

The interaction between AVs and non-motorized road users is a point of concern and should be minimized as much as possible. A study done by Blau et al. (*301*), using a stated-preference survey and random parameters logit model, suggests that under driverless vehicle conditions, the probability of choosing a separated bike lane by a bicyclist is more than doubled. Mode separation can reduce AV disengagements and boost the safety and confidence of bicyclists as AV performs better on roads with formal rules and clear boundaries (*300*).

Regarding the above-mentioned issues, experts in the field of AV were asked about their views on colored bike lanes and segregated bike lanes. Their suggestions along with recommendations are listed below:

- Colored Bike Lanes: A typical colored bike lane is shown below in Figure 77. The majority of the responders agree that coloring a bike lane will help both the AVs as well as human drivers. Coloring becomes more significant in cases where AVs are operated based on machine vision. Coloring a bike lane also helps AVs to separate it from drivable areas. In contrast, one of the responders argued that coloring is beneficial only for human drivers and AVs should be able to recognize bicyclists even if the bicycle lane is not colored. Moreover, coloring the pavement is expensive and difficult to maintain. Table 53 below represents the distributions of responders regarding the importance of colored bike lanes. It is worth to mention that TxDOT currently does not use colored bike lanes.

Figure 77 Colored bike lane. Source: NACTO

Table 53 Significance of colored bike lanes

S. No.	Category	Number of responses
1	For both (human drivers and AVs)	17
2	For human drivers only	1
3	Not necessary	2
4	Not sure	8

- Segregated Bike Lanes: The AV community believes that segregated bike lanes are eminent for bicyclists' safety. AVs might find it difficult to detect bicyclists without physical barriers. In urban areas where a multimodal transportation system is preferred, a segregated bike lane is recommended provided enough Right-of-Way (ROW) is available. If ROW is not available, imposing lower speed limits in those areas can be beneficial as it provides more time to the perception systems of an AV to find the bikers and essentially slow down. Moreover, educating the bicyclists, about biking policies, and the importance of using a helmet while riding can come in handy. One of the experts suggested that biker's advocacy groups do not want them to be separated from the main road and want to travel in the same lane by sharing it with motorized vehicles.

Others: Disengagements in AVs and Roadside Barriers

Disengagements in AVs: Manufacturers of AVs participating in the Autonomous Vehicle Tester (AVT) Program and the AVT Driverless Program must submit annual reports detailing how often their vehicles disengaged from autonomous mode during tests (due to technology failure or situations requiring the fallback-ready user to take manual control of the vehicle to operate safely) (*299*). Technology failure can occur due to various discrepancies, such as planning discrepancy: resulting in incorrect trajectory estimation, or perception discrepancy: failure to detect the object correctly. With an increase in trial runs these discrepancies can be addressed. Moreover, some fundamental measures that can be applied to prevent such discrepancies were discussed with the AV experts that are listed below:

- Data sharing between various AV developers: Various AV developers should share data and learn from each other. This will help to decrease the time required for an AV company to increase its ODD.
- Simulation based on aerospace industry: Aero industry does not test their system individually as an object moving in a space, rather they simulate each flap/each part. Hence, advanced physics-based simulation rather than a regular approach is needed.
- Simulations can be carried out in a protected environment having human drivers who make bad choices.
- Classify and categorize disengagements.
- Educating the public: AVs have the potential to reduce crashes and increase traffic efficiency. However, this is not possible without proper human education regarding AVs. The non-conformity of human drivers and their tendency to break traffic rules will push the deployment of AVs further back. Hence, the public should be educated regarding AVs.

Roadside Barriers: Roadside barriers are longitudinal devices that are used to separate travel lanes and motorists from natural (tree, hill, etc.) or man-made (culverts) obstructions (*302*). However, some roadside barriers get unified in their surroundings due to their contrast and machine vision fails to detect them, particularly in severe weather and poor lighting (*303*). The AV experts have made several comments on the challenges and possible solutions regarding the contrast of these roadside barriers that are listed below:

- Providing higher contrast to barriers in comparison to their adjacent road surfaces.
- Well-marked concrete barriers with retroreflective striping to improve visibility in all weather conditions.
- Vegetation growing on side of the roadway can obscure the roadside barriers and cause a problem.
- Lower height barriers pose a challenge: The barriers that are being used should be visible by the machine vision.
- Spacing of barriers: Minimum standard should be followed while placing barriers.
- Improvement in AI algorithms: The AI algorithm used to detect roadside barriers should be more robust.

CHAPTER 7: INNOVATIVE PARKING SOLUTIONS UNDER AV SCENARIOS

The global driverless auto market is growing rapidly, thanks to advancements in 5G technology. It is expected to experience a compound annual growth rate of 18.06% between 2020 and 2025 (*304*). The term "autonomous" can only be used to describe a vehicle system when it is able to complete all dynamic driving tasks in any driving environment. Driving requires many different functions, such as localization, perception, planning, control, and management. Autonomous driving technology is expected to make transportation safer, more sustainable, and more convenient. An autonomous vehicle (AV) is a vehicle that can sense its environment and navigating without human input. When AVs can replace human drivers, they will be able to perform five basic operational functions: localization, perception, planning, control, and management of the vehicle (*305–307*). In other words, AVs will have certain advantages over regular vehicles in terms of technology, including the ability to drive in formation (platooning), better fuel efficiency, eco-driving, adaptive cruise control with queue assist, crash avoidance, lane keeping, lane changing, valet parking or park assist pilot, traffic sign and signal identification, cyclist and pedestrian detection, and safe maneuvering at intersections or roundabouts. Modern urban environments these days include parking as a necessary component and significant land usage. Parking impacts traffic operations and congestion, contributes to the aesthetics of cities and suburbs, and is a crucial element of urban street and transportation systems. Parking lots and parking space availability often cover two factors. The first is parking accessibility in residential areas, and the second is business parking management. Parking accessibility affects the mode and route of travel, which has an impact on the viability and competitiveness of commercial sectors (*308*, *309*). Parking-related problems affect the entire urban region and not just the core downtown/city centers and thus planning for urban transportation must include effective parking management. As typical vehicle spends 95% of its lifetime parked, parking must be considered when building transportation systems. Major urban centers around the world are experiencing severe problems with such static traffic. In many nations, valuable real estate has been converted into parking garages due to the growing need to keep automobiles. In the United States, the total parking takes up an area larger than the entire state of Connecticut (6500 square miles) (*310*, *311*). A vehicle that is not on the road is parked somewhere else and consuming space. Most importantly, when there is improper parking management, such situations become challenging to handle. For large metropolitan regions, vehicles are typically parked in the street in the lack of parking lots. On highways, drivers frequently park their vehicles in front of rest stops along the side of the road. The road user's safety and security are in danger in either situation. The issue of parking in cities and urban regions is one that both the public and experts address frequently and is becoming more and more relevant. The main cause of city parking issues has been attributed to an imbalance between parking supply and demand. Additionally, the parking system is crucial to the efficiency of urban transportation, and its absence is directly related to environmental pollution, traffic accidents, and congestion. Parking problems are a frequently disregarded part of urban planning and transportation, even though effective parking systems can also improve urban mobility and the environment while improving inhabitants' quality of life. The focus on vehicle-related problems has typically been on fatal collisions, air pollution, or traffic congestion; relatively little is said about the vast amount of space that vehicles take up in American cities. Then there is the space that individual vehicles take up. The typical vehicle is 80 percent empty while a single person is behind the wheel. Additionally, most of the travel time in congested urban environments is spent with idle autos. Parking space is undoubtedly necessary at the trip origin and destination. In the United States, there are one billion parking spaces, or four spots for each automobile. In addition, there are all the paved highways that cross our cities. Add it up, and many downtowns devote 50 to 60 percent of their scarce real estate to vehicles (*116*).

Another inconvenient part of personal vehicle travel is finding a spot near the destination to park the vehicle. Empirical evidence shows that travelers spend an average of 20 min to find a parking space in metropolitan areas (*310*, *312*, *313*). This parking search process is not only frustrating to drivers, but it also works against city planners' efforts to minimize congestion. The limited parking space causes travelers to start searching when they get close to their destination and cruise until finding a spot. The travelers who search for parking account for approximately 30% of traffic on major streets. When it comes to management, planning, and design, urban planners should look for more effective and creative parking options (*314*). The way self-driving vehicles behave on the road can potentially impact traffic congestion in cities, both in terms of the amount of traffic and the capacity of the roads. This is because self-driving vehicles often have different driving characteristics than traditional vehicles, such as different headways. These differences can impact traffic on a small scale by affecting the capacity of the roads, and on a large scale by influencing travel demand. Both effects are dependent on how the market develops for self-driving vehicles, which will impact the rates at which they are adopted in urban areas (*315*). AV industry leaders are reassessing ways to reduce the parking footprint by transforming conventional parking lots into automated parking facilities that can store more AVs (relative to standard vehicles) in smaller spaces considering the high social cost of providing parking. The advent of autonomous vehicles (AVs) will revolutionize future transportation. The introduction of autonomous vehicles (AVs) will transform transportation in the future. Along with improved mobility for the young, old, and disabled, safety is expected to be the main benefit. The effects on the environment are less certain. Although AVs may contribute to urban sprawl, they also present opportunity to reconfigure streets, so they are more conducive to cycling and walking while also improving vehicle efficiency. Automated valet parking removes human drivers challenges of having to squeeze through a narrow gap in the door when the vehicle in the neighboring space is too close for comfort. Instead, automated valet parking users simply summon their vehicle to the pickup point via an app and get in there. Since parking is done fully autonomously, vehicles do not need much clearance in automated parking spaces (*316*). To reduce expenses for the owners, AVs have the capacity to cruise (i.e., circle while waiting for a passenger) which could add to existing congestion, especially gridlock. The usage of autonomous private vehicles or taxis may lessen the need for parking in urban core areas, freeing up such spaces for other types of commercial activity, which could boost urban density in Central Business Districts (CBD) locations (*317–319*).

Autonomous Vehicle and Significance

The way self-driving vehicles behave on the road can potentially impact traffic congestion in cities, both in terms of the amount of traffic and the capacity of the roads. This is because self-driving vehicles often have different driving characteristics than traditional vehicles, such as different headways. These differences can impact traffic on a small scale by affecting the capacity of the roads, and on a large scale by influencing travel demand. Both effects are dependent on how the market develops for self-driving vehicles, which will impact the rates at which they are adopted in urban areas (*315*). AV industry leaders are reassessing ways to reduce the parking footprint by transforming conventional parking lots into automated parking facilities that can store more AVs (relative to standard vehicles) in smaller spaces considering the high social cost of providing parking. The advent of autonomous vehicles (AVs) will revolutionize future transportation. The introduction of autonomous vehicles (AVs) will transform transportation in the future. Along with improved mobility for the young, old, and disabled, safety is expected to be the main benefit. The effects on the environment are less certain. Although AVs may contribute to urban sprawl, they also present opportunity to reconfigure streets, so they are more conducive to cycling and walking while also improving vehicle efficiency. Automated valet parking removes human drivers challenges of having to squeeze through a narrow gap in the door when the vehicle in the neighboring space is too close for comfort. Instead, automated valet parking users simply summon their vehicle to the pickup point via an app and get in there. Since parking is done fully autonomously, vehicles do not need much clearance in automated parking spaces (*316*). To reduce expenses for the owners, AVs have the capacity to cruise (i.e., circle while waiting for a passenger) which could add to existing congestion, especially gridlock. The usage of autonomous private vehicles or taxis may lessen the need for parking in urban core areas, freeing up such spaces for other types of commercial activity, which could boost urban density in CBD locations (*317–319*).

AV *Impact on Urban Design*

Many Researchers have found that modeling scenarios are a useful tool for planning and structuring changes, evaluating outcomes of alternative solutions, in an uncertain and rapidly changing environment. Scenarios can help decision-makers think about long-term transport and urban development policy. For example, existing literature presents a scenario system where autonomous driving is differentiated into three types of cities: regenerative/intelligent city, hypermobile city, and endless city (*119*, *160*, *161*).Table 54 presents the overview and characteristics of scenario system mentioned earlier, based on form of autonomous driving, urban land use and driving factor.

Table 54 Overview of Scenarios

Scenario	Form of autonomous driving	Urban land use	Driving factor
Regenerative city	-Flexible, multimodal, and networked public transport system as the backbone of urban mobility -Semi-autonomous vehicles (autopilot) on freeways	-Formation of intermodal mobility hubs -Reduction in land consumption for urban parking spaces due to new parking systems	-Technological development (in the energy system) -Conscious and responsible use of resources -Legislation and acceptance promotion by the state
Hypermobile city	-Highly networked (autonomous) mass taxi systems -AVs on freeways with high transit volumes or along commuter routes, on reserved “guided lanes”	-City centers of high density -Growth of low-density suburbs	-Increasing acceptance of Information Comm. Technology (ICT) due to its lifestyle and commercial benefits -Cooperation of state and private sector in developing the necessary ICT technologies
Endless city	-Predominantly vehicle-dominated -Low level of networking with public transport -No notable developments in automated driving	-Suburban growth -General decline of settlement densities	-Limited state power to steer development -Technological development restricted to efficiency gains in discrete areas

A qualitative review of future parking demand by Klynveld Peat Marwick Goerdeler (KPMG) Global (*162*) based on a set of three potential scenarios for worlds where AVs are: privately-owned; shared with single-occupancy; and shared with multiple occupancy has been summarized in the table below (Table 55). But the main purpose of several scenario studies is not to predict the most plausible or likely future but to illustrate the range in different possible futures. Such studies are always a simplification of reality since they cannot include all possible factors or developments that will occur (*159*).

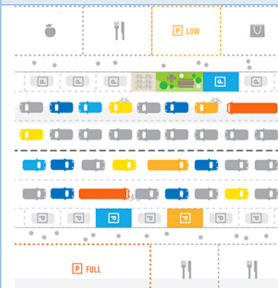
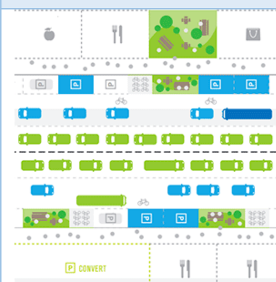
Table 55 The Impact of AVs on Parking Scenarios

Impact	Scenario 1: Privately-owned	Scenario 2: Shared with single occupancy	Scenario 3: Shared with multiple occupancy
Number of vehicle parks	Equivalent to today, subject to whether vehicles can re-position themselves in different locations on the public road network	Lower than Scenario 1. Fewer vehicles require parking and duration of stay reduces.	Significantly lower than Scenario 1. Significantly fewer vehicles require parking.
Location	Basic autonomy will permit drop-off and parking, lots still need to be located near destination. Higher autonomy will allow drop-off at destination and parking located elsewhere	Vehicle parks could be in cheaper, out of town locations during periods of lower demand.	Vehicle parks located at key destinations with high demand to provide spare vehicles and servicing centers.
Parking revenues	Same as today or greater	Reduced due to less time spent in vehicle park and fewer parked vehicles.	Significantly reduced due to less time in vehicle park and significantly fewer parked vehicles.
Type of facility	Same as today. Opportunity to widen service offer	Vehicle parks transformed to become service centers and waiting areas until AV is requested by 'user'	
Operational capacity	Capacity optimized (more vehicles, same space)	Fewer spaces needed than Scenario 1	Significantly fewer parking spaces needed than Scenario 1
Rate of change/ implementation	Gradual implementation of AV floors (e.g., one floor at a time)	Rapid (i.e., once Uber decide to do this it will happen quickly)	Subject to local market conditions and familiarity with ridesharing

San Francisco' Smart City Concept

San Francisco was named as one of seven finalists in U.S. DOT's recent Smart City Challenge (*320*). There were initially 78 entrants in the competition, which are vying for $50 million to support technology-based initiatives to improve traffic and reduce collisions. The DOT will announce a finalist in July. San Francisco' plan includes provisions for repurposing parking facilities into affordable housing and public open spaces (see Table 56).

Table 56 Transition Scenarios Illustration

Model	Attributes	Design
Ownership Model	• all modes operate independently. • congestion, pollution collisions, waste, noise. • public space dominated for parking and road. lack of funding to maintain system. • lack of supply means long wait times and high prices for on demand services. • lack of social equity	
On-Demand Services	• supply greatly increased for on-demand services but still out of reach for most. • sharing becomes viable. • vehicle/bike and pool services emerge reducing costs. • shared delivery services emerge reducing costs for suppliers and receivers	
Shared On-Demand	• Most vehicles are shared, modes are integrated, trip costs are low enough for most users to participate. • Supply is closer to being satiated with shared services and parking demand peaks.	
Share and connected	• Connected technology optimizes the shared services • Collision avoidance and speed reduction reaching Vision Zero • Parking and street use demand reduces enough to re-purpose some space to temporary uses. • More equitable transport • Built out bike network	
Shared Electric Connected Automated Model (SECAV)	• SECAV services are fully optimized • Fatalities zero, Vision Zero Reached • Pollution, Noise, costs, impact minimized • Social equity and access significantly improved • Parking structures repurposed for affordable housing; street becomes shared spaces for all	

Parking Standards in USA

General Design Criteria-On Street Parking

The kind of on-street parking that is chosen should consider the particular purpose and width of the street, the nearby land use, traffic volume, as well as current and future traffic operations. Due to the different lengths of the vehicles and the sight distance issues with vans and recreational vehicles, angle parking poses unique challenges. Such vehicles' added length may obstruct the path of travel. The factors to consider in a parking lot layout include parking lot size, pavement, parking space angles in consideration to level of vehicle turnover, accessibility requirements (ex. ramps), lighting design, landscaping, drainage, and overall traffic flow including that of pedestrians. The average parking space in North America is between 8.5 and 9 feet wide and 18 feet long. Parking lot aisles often feature a gap between rows of 14 to 24 feet, depending on whether they are one-way or two-way. Additionally, most parking spaces will be at an angle of 30°, 45°, 60°, or 90° to the curb. For vehicles moving in opposite directions to do so safely, two-way aisles must be wider. As a result, most two-way aisles are at least 20 feet wide. One-way lanes, on the other hand, have more leeway to be narrower, though they may still require larger widths, depending on the second important factor below.

- The size of a parking place can vary depending on local laws and variables including parking lot volume, angle to curb, and accessible amenities like a handicapped area. Parking lots must have a specific number of spaces designated as handicap accessible, along with the appropriate signage and location. In addition to the normal measurements, the dimensions must adhere to special requirements. The standard requirement for handicap parking spaces is that they be at least 14 feet wide to accommodate wheelchairs and other equipment. The length of a space could also need to be extended to make room for handicapped-accessible vans.

Most vehicles will parallel park between 150 and 300 mm (6 to 12 in) from the curb face, taking up on average about 7 ft (2.1 m) of real estate on the street. The desirable minimum width of a parking lane is 8 ft (2.4 m). However, a parking lane width of 10 to 12 ft (3.0 to 3.6 m) is preferred to give better clearance from the traveled way and to permit usage of the parking lane as a through-travel lane during peak hours. This width is also sufficient to accommodate delivery vehicles and serve as a bicycle route, allowing a bicyclist to maneuver around an open door on a motor vehicle. On urban collector streets, the demand for land access and mobility is equal. The desirable parking lane width on urban collectors is 8 ft (2.4 m) to accommodate a wide variety of traffic operations and land uses. To provide better clearance and the potential to use the parking lane during peak periods as a through-travel lane, a parking lane width of 10- to 12-ft (3.0- to 3.6-m) is desirable. A 10 to 12 ft (3.0 to 3.6 m) parking lane will also accommodate urban transit cross section elements operations. On urban collector streets within residential neighborhoods where only passenger vehicles need to be accommodated in the parking lane, 7-ft (2.l-m) parking lanes have been successfully used. In fact, a total width of 36 ft (10.8 m) , consisting of two travel lanes of 11 ft (3.3 m) and parking lanes of 7 ft (2.l m) on each side, are frequently used (AASHTO (*321*)). On-street parking is generally permitted on local streets. A 26 ft (7.8 m) wide roadway is the typical cross section used in many urban residential areas. This width assures one through lane even where parking occurs on both sides. Specific parking lanes are not usually designated on such local streets. The lack of two moving lanes may be inconvenient to the user in some cases; however, the frequency of such concerns has been found to be remarkably low. Random intermittent parking on both sides of the street usually results in areas where two-way movement can be accommodated. The cross-section specification or considerations for urban street parking has been summarized and tabulated below (see Table 57).

Table 57 On-street Parking and Cross-sectional Dimension Standards

No	Street type	Sidewalk Width	Curb Clearance	Parking Lane Width	Length of Parking Space	Travel Lanes Width
1	General	5 feet (minimum)	6 inches	8 feet (minimum)	20 feet	11- feet
2	General	8 feet (schools, sporting complexes, some parks, and many shopping districts	6 to 12 inches	10 to 12 ft (If sufficient RoW available)	20 feet	11-12 feet
3	Collector Street (Urban)	5-8 feet	9 inches	10 to 12 ft (If sufficient RoW)	20 feet	11-12 feet
4	Collector Street (Residential	5-8 feet	9 inches	10 to 12 ft (If sufficient RoW available)	20 feet	11-12 feet
						(Extracted from AASHTO Green Book)

Autonomous Vehicle Parking

Autonomous vehicle parking refers to the ability of the vehicle to park itself from the starting point to the finishing position with the correct orientation. While parking a vehicle may seem simple to a human driver, it is difficult to incorporate similar understanding into a machine. An autonomous vehicle may not function well if it is not constructed correctly due to the highly dynamic environment. The driver assistance capability known as SAE Level 4 is necessary for vehicles to be able to automatically navigate themselves to and from far-off parking spaces. Several nations have strict laws governing the safety precautions for driverless vehicles (SAE Level 4 and 5). Since the driver is not necessary in a Level 4 system like Intelligent Park Pilot, such systems are appropriate for local driverless taxi services. In the case of Intelligent Park Pilot (*322*), that automated operation is very local because it is only available in the vicinity where the vehicle's sensors are supplemented by additional sensors in the infrastructure to ensure a thorough understanding of the environment. Finding a legal route that a vehicle can travel on to get to its intended parking space is the main goal of every parking challenge. Before planning a workable approach, it is important to consider the sort of parking that will be used, such as parallel, garage, or diagonal parking. It can be done in two ways: offline path planning and online path planning. Planning a route offline or online are the two methods available. Offline path planning begins when the vehicle is fully aware of its surroundings, parking spot, obstacles, and ultimate destination. The vehicle only needs to create a legitimate trajectory leading to the destination; after that, it must carry out the path tracking. It is helpful in environments that are static or slowly evolving. However, an online path planning strategy for the vehicle must be adapted by the autonomous parking system for a dynamic and uncertain environment. When operating in online mode, path planning is done concurrently with (a) traveling in the direction of the goal and (b) observing the surroundings, including any changes. A sensing component must be installed in the vehicle for it to continuously collect data. The vehicle is finding its parking space as it is moving, thus it is important for the partially known surroundings since the path must be updated in accordance with any new information (*307*, *323*, *324*) (see Figure 78). Self-driving vehicles face many challenges, such as understanding the road and other vehicles around them.

Lane detection is a crucial part of this, as it allows the vehicle to position itself correctly and make decisions about where to go. AV Readiness programs must be about integrating AV's successfully into the transportation system to realize the significant societal benefits, leveraging their unique capabilities to better operate the system and ensure consistency and interoperability across jurisdictions (*325*, *326*). As illustrated in Figure 78, the algorithm of the autonomous valet parking system involves scenario perception, vehicle positioning, guidance function, free space search, and parking maneuver. The first function includes the positioning system on the digital map. When the vehicle is in the desired zone, it looks for free spaces simultaneously with the previous functions. This is the so-called Free space search function. Once identified, the parking maneuver type is defined, the vehicle proceeds to the starting point of the maneuver and performs the parking maneuver (Parking maneuver function, which sends the orders to the low-level control layer of the autonomous vehicle). If the whole route is completed without finding a suitable parking space, the vehicle stops at the exit and a human driver must take control again (*324*).

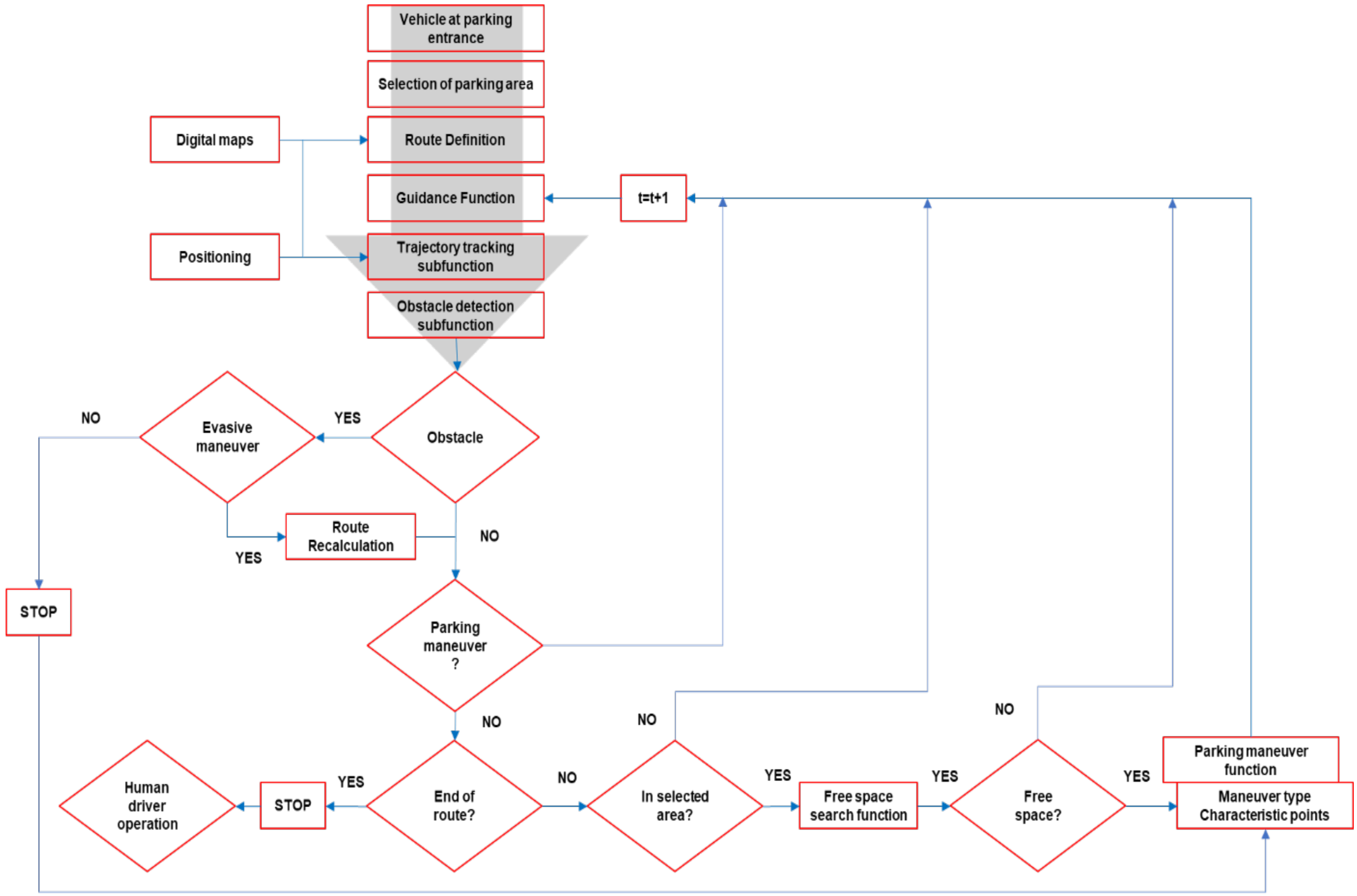


Figure 78 Automatic Valet Parking Driving Tasks Flowchart, Source: Jiménez et al. (*324*)

Empty Trips/ *Cruising*

An empty repositioning trip is a trip that an AV (AV) makes without any passengers, to avoid parking at the destination or to make the vehicle available to other members of the household. These types of trips are likely to travel in the opposite direction than most person-trips. In other words, with AVs, there is no need to park at the user's destination. The AV can return home, park remotely, or even cruise around. It is expected that fully AVs will be repositioned to avoid parking costs, which influences the destination and/or mode choice decisions of travelers. For instance, currently, travelers may have to pay large parking fees at their destination, especially if their destination is in a CBD. However, if they were using an AV, the AV could drop them off at the destination (at the parking entrance or at a designated drop-off zone), and then the AV could go on an empty repositioning trip to reduce or completely avoid parking costs at the destination. (*120*). In practice, the decisions by AVs regarding parking location and whether to park or cruise are likely to be cost driven and based on the relative costs of each option. As illustrated in Figure 79, the parking dynamics of AVs involve two states: parking-related states and parking-related transition events.

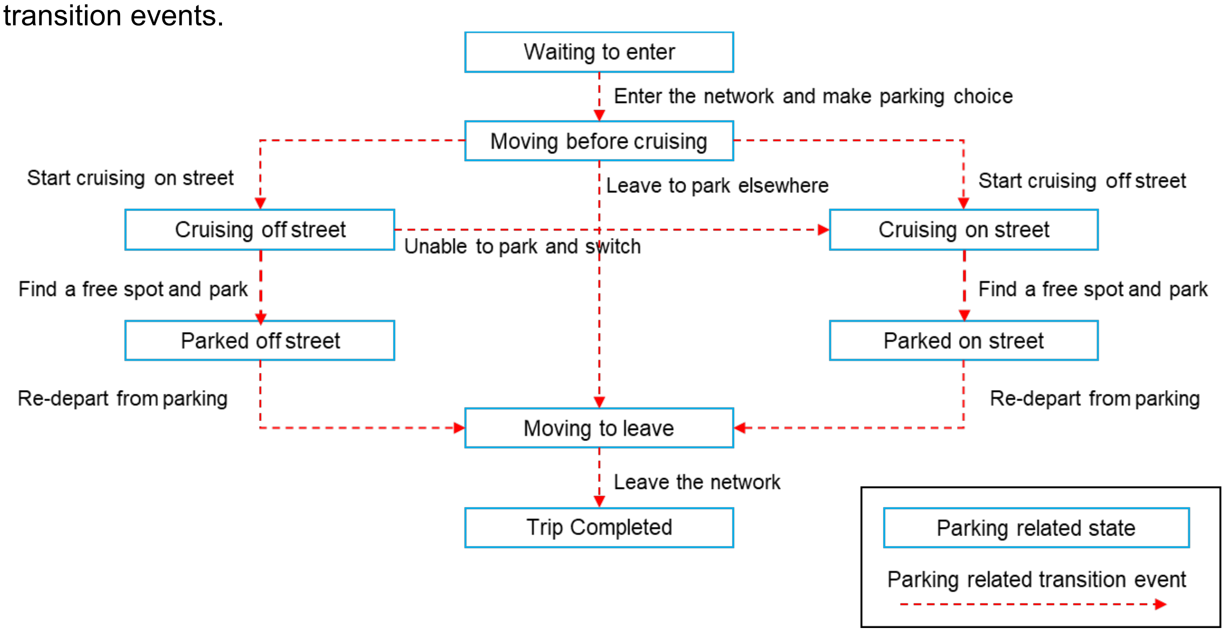


Figure 79 Parking Dynamics

Considering the land value, constructing large parking facilities for AVs outside the city centers and encouraging AV owners to park their vehicles at such parking facilities by choosing appropriate parking costs at each location would help convert parking in CBD to commercial or efficient spaces (*121*). The demand for parking in the main CBD is moved towards a less intensive economic activity areas, so that land in business districts can be utilized more efficiently (*122*). This way, demand for on-street parking at a short distance from the final trip destination is expected to decrease, freeing space for other land uses, especially for congested areas with low on-street parking supply and high demand during peak periods, provided additional vehicle miles will be travelled. Existing parking facilities designs can be modified to accommodate the AV which has better space utilization than HDVs. Researchers (*327*) found that each new autonomous vehicle on the market saves an estimated $250 in parking costs. This is primarily due to the reallocation of parking space from busy areas, like the CBD, to more remote areas. With autonomous vehicles, land that is currently used for parking and transport can be converted to other uses, like active modes of transportation, such as walking and cycling, or construction of greener space. Nourinejad et al. (*117*), using high-level strategic design of vehicle-parks found that AV parking can decrease the need for parking space by an average of 62% and a maximum of 87%

Parking and Safe*ty*

For Level 4 and Level 5 true self-driving vehicles, there will not be a human driver involved in the driving task. All occupants will be passengers. The machine or system is doing the driving. Detecting other vehicles that are nearby to a self-driving vehicle is somewhat straightforward for the AV driving system. Usually, other vehicles are relatively sizable, and a self-driving vehicle can make use of its on-board video cameras, radar, LIDAR, ultrasonic units, and other sensory devices to figure out that a vehicle is in the driving scene of interest. Smaller objects and modes are an added challenge for machine detection relative to vehicles or larger modes. Though it might seem like the system should be able to detect a bicycle in the same way that it detects a vehicle, there are some significant differences. For one, a bicycle is much smaller than a vehicle, which can make detection more challenging for the AV. Second, a bicycle does not have a solid metal frame like a vehicle, which can cause difficulty in understanding that it is, in fact, seeing a bicycle. Detecting bicycles is an important part of the AV system to avoid significant safety concerns. Pedestrian and other non-motorized traffic along with roadside infrastructures has a huge impact on the AVs driving behavior on urban streets. Self-driving vehicles' ADAS systems must be able to recognize dynamic (pedestrians, non-motorists, etc.) and static (traffic posts, roadside infrastructure, curb encroachment, etc.) entities to avoid collisions or conflict with them. Vision has been a crucial factor in this area of research for more than a decade. Finding the pedestrians is simply a preliminary step since the real question is whether the ego-vehicle will collide with a pedestrian if preventive measures are not implemented. For example, using Figure 1 Left as a model, a pure pedestrian detection approach would alert the driver that a pedestrian may be in danger depending on the location of the pedestrian relative to the road ahead of the ego-vehicle, the distance between the pedestrian and the vehicle, and the motion of the vehicle (direction and speed).To avoid a collision and conduct safe and comfortable maneuvers, it is necessary to know as soon as possible if a detected pedestrian intends to cross the path of the ego-vehicle (expecting the vehicle to slow down or brake). This will also help automobiles behave more considerately around pedestrians. (*328*, *329*). Predicting whether a pedestrian will cross the street is more difficult if you do not have a model of whether the pedestrian wants to cross the street. A pedestrian might stand at the side of the road for several seconds waiting for the right moment to cross, so a self-driving vehicle needs to know whether the pedestrian is trying to cross the street, not just whether he or she is going to do so in the very next second. Correctly interpreting scenarios with lateral oncoming people is one of the most difficult challenges. Pedestrians can abruptly shift their walking direction or stop or start walking due to the great unpredictability of their movement patterns. Since incorrect activations could cause severe harm involving other traffic participants, present systems are therefore designed conservatively by lowering benefit. A solid pedestrian intention identification and path prediction system is very important to handle this circumstance.(*328*, *330*).

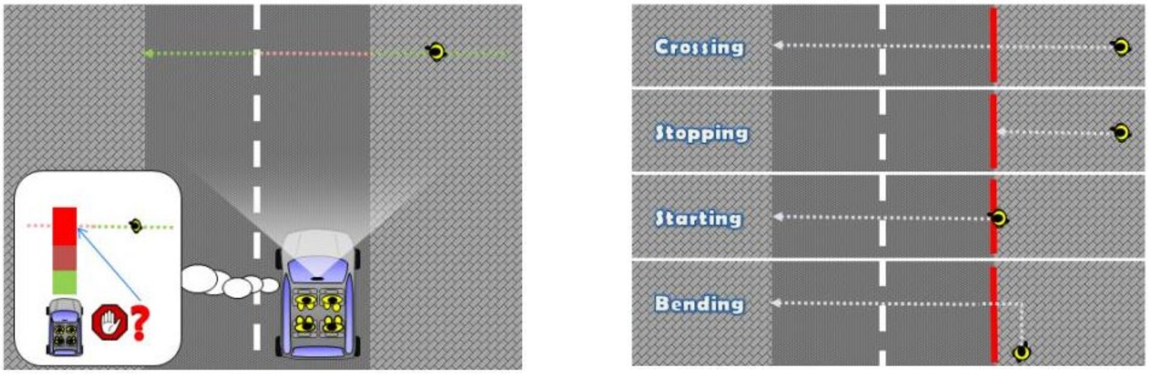


Figure 80 Pedestrian travelling on the sidewalk will be perceived by the ADAS system

The illustration in Figure 80 (left) shows: ADAS/ADS system anticipating as much as possible the intention of a pedestrian allows for safer and more comfortable maneuvers, for instance, to know if the pedestrian will cross the street while approaching it from the sidewalk or, more generally, if they will enter a dangerous region that the ego-vehicle can calculate as their expected driving path.; The illustration in Figure 80 (right) shows: different situations taking the curbside (red line). From top to bottom:

I. a pedestrian will be **crossing** the road without ***stopping,***
II. a pedestrian walking towards the road will be ***stopping*** at the curbside,
III. a pedestrian that was stopped at the curbside is ***starting*** to walk for entering the road,
IV. a pedestrian walking parallel to the curbside (parallel to the trajectory of the ego-vehicle) will be ***bending*** towards the road. plotted the pedestrian walking away from the ego-vehicle but walking towards the ego-vehicle and ***bending*** would fall in the same category.

In fact, the user experience video data analysis directly highlighted the impact of pedestrian movements on AV driving behavior, which was visible in a variety of driving scenarios, from off-street parking lots to pedestrian on median. Speed dropped from 45 mph to almost 27 mph as a result of the pedestrian waiting in the median in a very short span of time (331) as shown in Figure 81. Prior research on pedestrians' interaction with human-driven vehicles has highlighted the importance of non-verbal communication to ensure safety.

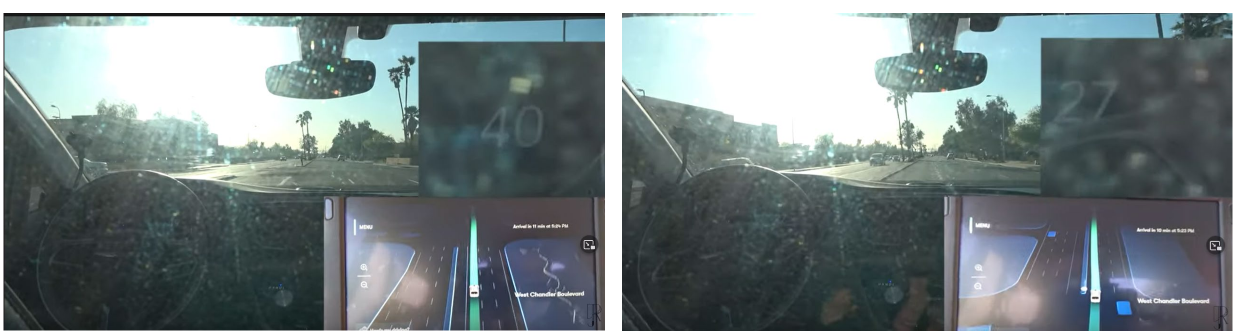


Figure 81 Pedestrian Impact on AV Behavior, Source: JJricks Studios

Off-street Parking Challenges

Even without shared ownership, autonomous vehicles might park themselves, reducing the need for parking to be built adjacent to every location and home and freeing up a significant amount of urban territory. Less land set aside for parking vehicles might be used for other purposes, such residential development, which would lower the cost of housing. Lead AV developers from Google

Waymo Ridesharing services says that parking lots are uniquely challenging as compared to surface streets due to the lack of standardized rules for how people should move about within them. Some of the other parking challenges faced by the self-driving vehicles are summarized below, and these could impact the future design criteria of parking lots and related infrastructures.(*332*).

- Although there are official rules in parking lots, people tend to behave however they want. Carts can be left in the wrong area, shoppers carrying boxes may sprint across a busy road without using a crosswalk, and vehicles may turn in the wrong direction or drive over vacant parking spaces.
- “A self-driving vehicle is not social,”: This means that a self-driving vehicle cannot understand social cues, like a wave, that humans use to communicate. This can be a problem because it means the vehicle might not be able to understand when someone is trying to tell it that a parking spot is about to open.
- AV manufacturers and engineers can control dynamic factors such as vehicles reversing out of spaces, pedestrians crossing the road when they should not (or in the path of the vehicle), and people carrying heavy objects that may alter how the vehicle's perception system perceives them. According to one engineer at Google Waymo, the vehicles will have to evaluate and forecast numerous items' behavior simultaneously as you turn the dial to increasing complexity. That is difficult for sensors.
- The vehicles need to be taught to be cautious near dumpsters, especially those with swinging doors and cinder-block walls around them. This is because people or carts can come out from behind the walls and the self-driving vehicles' lasers or cameras is unable to “see” through concrete, just like human eyes cannot.

Methodology

Presently there exists several unanswered questions regarding the make-up of the vehicle fleet during the period from 0 to 100% AVs, such as what automation functions are technically possible, legal, and used by users, for various road environments and at various stages of the introduction of AVs. Since multiple types of AVs will exist and may coexist during the transition period, it is necessary to take this into account in traffic simulation studies. Microsimulation models were developed to understand the impact of the roadway geometries (cross section and longitudinal) on future traffic consisting of mix of HDVs and AVs. For complicated impacts and/or higher precision, leveraging microsimulation extensions such as PTV Vissim interface (such as COM interface, DRIVERMODELL.DLL, or DRIVINGSIMULATOR.DLL) where the precise methods can be implemented may be required. This is only practical, of course, if the algorithms behind decision-making and driving behavior are understood. This means that to accurately understand how AV Park in on-street/off-street parking spaces, the results of the microsimulation analysis need to be confirmed with real-world test cases. In addition, the offered model has simplified a number of potential heterogeneities, such as the potential variability in AV acceleration behavior, which could affect the details of the simulation results (*333*). Figure 82 illustrates the study framework leveraged in this parking analysis and recommendation study considering the drawbacks of the micro-simulation analysis. The study used micro-simulation to analyze the impacts of AVs on urban on-street parking facilities.

PTV VISSIM Suite was used for the micro-simulation. The micro-simulation results were used to make design recommendations to such facilities in terms of width reduction, infrastructure segregation, spatial distribution of pick-up drop area, and impact on traveling and parking lanes for various mixed traffic scenarios. Because of the large number of uncertainties and assumptions in terms of the precise impact of various levels on AV, using only micro-simulation tools for such analysis has significant limitations. Additional video data/user experience analysis was conducted in addition to a focused literature review and information search to forensically analyze the future impact of AVs on parking facilities and suggest practical recommendations for deployment for testing in urban streets.

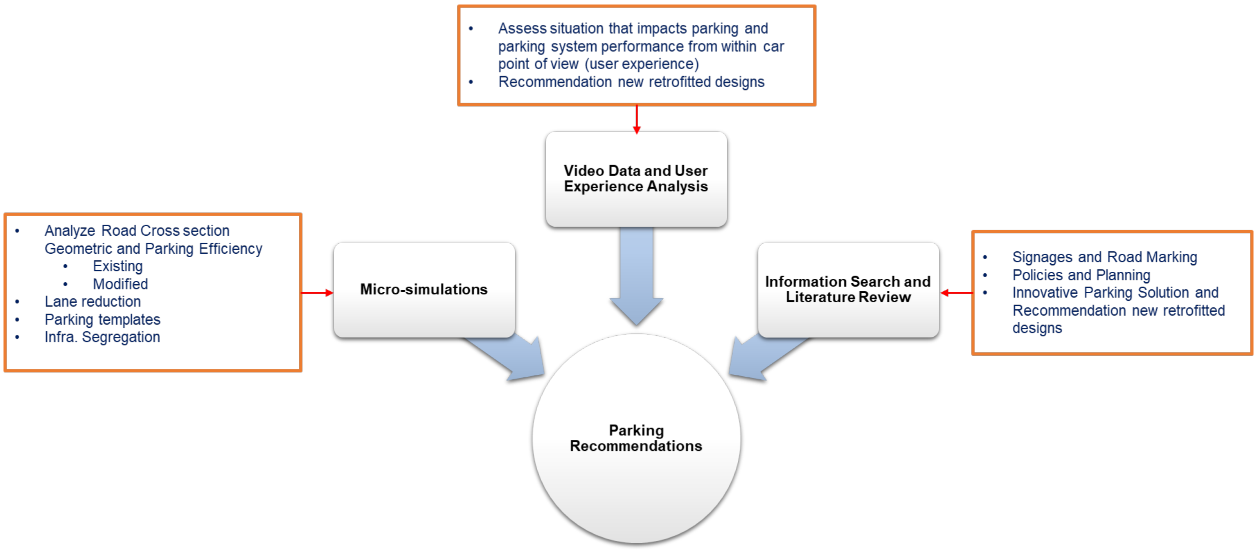


Figure 82 Study Methodology

Microscopic Traffic Simulation

Microscopic traffic simulation models are state-of-the-art tools in transport planning. By simulating the movements of every individual vehicle, the models provide indicators (travel time, queue length, vehicle throughput, etc.) describing the performance of road facilities. Traffic simulation models are typically applied for designing, testing, and analyzing road network sections with their traffic control facilities. They extend traditional highway capacity manuals (HCM) by providing methods for capacity analysis with varying demand, demand-actuated traffic control facilities, and coordinated signal control. Current microscopic traffic simulation models are designed for modelling vehicles with no automation. Hence, modelling the behavior of AVs requires model extensions. These extended models also need to be calibrated and validated which is a problem since the systems to a large extent do not exist yet. Some of the most used approaches in the past studies has been listed below:

- Simulation of automated driving behavior by adjustment of behavioral model parameters in the traffic simulation model
- Replacement of behavioral models in the traffic simulation model with AV driving behavior models
- Extension of the driving behavioral models with “nanoscopic” modelling of AVs, including simulation of sensors, vehicle dynamics, and driving behaviors

Changing the parameters of an existing behavior model for conventional vehicles to represent the driving behavior of AVs is one of the easiest and most popular ways to integrate AVs in traffic simulation models. In practice, this can be achieved be adjusting reaction time, gap-related parameters, acceleration parameters, and speed limit acceptance (*179*, *334*, *335*). This approach has the disadvantage that the behavioral models in the traffic simulation model were developed to mimic human driver behavior. Additionally, it is uncertain if the driving behaviors of AV can be modelled by simply adapting the parameters or if fundamental changes to the driving models are necessary. The advantage is that the unknown AV behavior easily can be specified in terms of changes in relation to human driver behavior, e.g., shorter reaction times and changed desired speed distribution (*333*). An AV class is a high-level description of the behavior and capabilities of the vehicles. The general assumption is that the main priority at each class is safety and that difference between the classes lies in the ODD and how “offensively” the vehicles can handle different road environments and traffic contexts.

- Basic AV: the first type of AVs with SAE level 4 capabilities only for one-directional traffic environments with physical separation with active modes. The behavior is in general quite cautious and risk minimizing.
- Intermediate AV: AVs with level 4 capabilities in some road environments and driving contexts. The behavior at more complex road environments and driving contexts is still cautious and risk minimizing while the behavior at less complex road environments and driving contexts can be less cautious and still be safe.
- Advanced AV: AVs with level 4 capabilities in most road environments and driving contexts. The advanced AVs can drive more “offensively” but still safe in most road environments and driving contexts but still need to apply a more cautious behavior in complex road environments and driving contexts (*336*).

SAE levels 1 and 2 refer to driver support systems that help with DDTs, which the driver is ultimately in charge of. At level 3, a driver still controls the vehicle, and an ADS completes the entire dynamic driving duty, although it can only function in a small ODD. Level 4, in which the ADS oversees driving, is an expansion of level 3. The AVs with level 4 capability for some ODDs are the main topic of this essay. The SAE levels do not, however, categorize between how driving behavior varies across levels or even within a level. For this, Olstam et al. (*333*) recommended two notions to define the level of automation:

- AV class (Basic AV, Intermediate AV, and Advanced AV)
- Driving logic (Rail-safe, Cautious, Normal, and All-knowing) for different road environments (Appendix 2).

NOTE: The important simulation and driving behavior parameters are summarized in APPENDIX 2 at the end of the document.

Micro-simulation was conducted on virtual urban street sections of fixed length and various cross-sections for travel lanes and parking lanes were with on-street parallel parking with standard dimensions was tested. The primary assumption for the parking microsimulation analysis is that manual driving has more implicit stochastics while AV driving is more deterministic. AVs, irrespective of their individual automation level definition, will behave cautiously or manually around parking lot facilities to ensure maximum safety of passengers as well as surrounding vehicles or pedestrian or other road users (see Table 58). The important driving parameter for human drivers and AVs are tabulated in Table 59.

Table 58 Recommended Specification of the driving logic

Road type	Basic AV	Intermediate AV	Advanced AV
Motorway	Cautious	Normal	All-knowing
Arterial	Cautious	Cautious/Normal	All-knowing
Urban street	Manual	Cautious	Normal
Shared space	Manual	Rail-safe2/Manual	Cautious

Table 59 Simulation Driving Behaviors

Driving Behavior	Manual Driving	AV Driving
Vehicle following model	Wiedemann 74	Wiedemann 74
Average stand still distance (feet)	6.56	3.28
Additive factor for security distance	2	1.5
Multiplicative factor for security distance	3	0
Standstill distance	4.92	4.92
Gap time distribution	Stochastic	0.45 s
'Following' distance oscillation	13.12	13.12
Reaction time distribution	Stochastic	Constant

Test Scenarios

The description of the test network and general cross section dimensions for the different tested cases are tabulated below Table 60 and Table 61)

Case 1: Desired Design Parking Lane Width (12 feet)

Table 60 Case 1 Network Features

Network Attributes	Value
Parking Lane Width	12 feet
Travelling Lane	12 feet
Parking lot type	On-street parallel
Parking space width	12 feet
Parking space length	20 feet
Parking Duration	Average 5 mins (Normal Distribution)
Traffic Volume	50 vehicles per hour (free flow condition)
Block Time Duration	3 to 6 seconds Empirical Distribution

Case 2: Minimum Parking Lane Width (8 feet)

Table 61 Case 2 Network Features

Network Attributes	Value
Parking Lane Width	12 feet
Travelling Lane	12 feet
Parking lot type	On-street parallel
Parking space width	8 feet

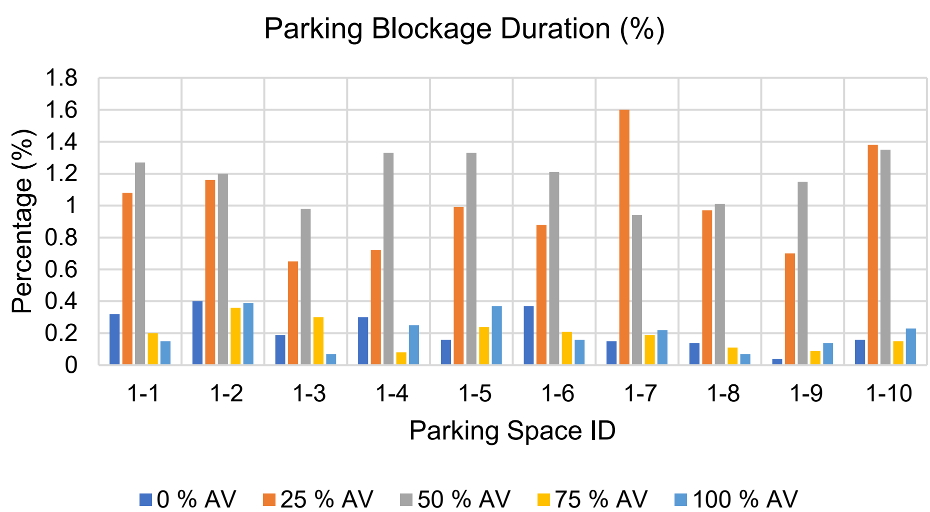
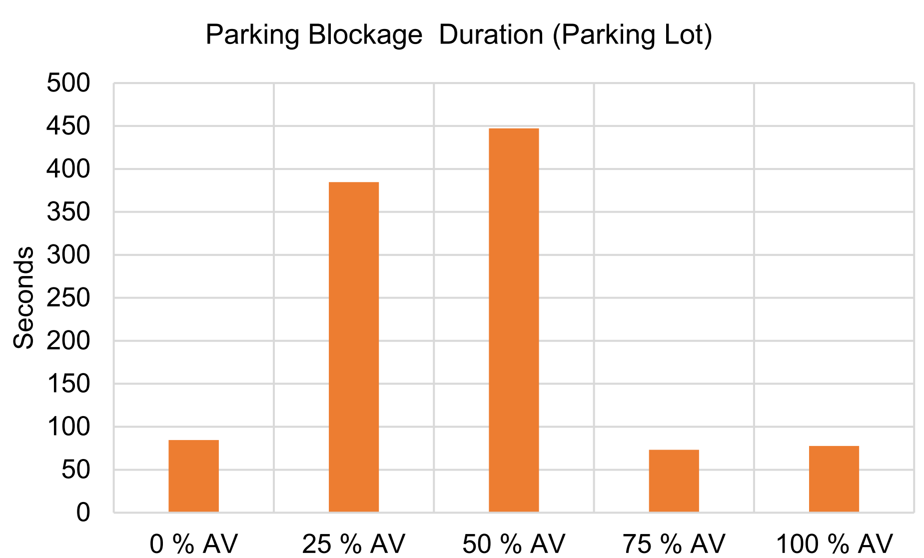
Parking space length	20 feet
Parking Duration	Average 5 mins
Traffic Volume	900 vehicles per hour (free flow condition)
Block Time Duration	3 to 6 seconds Empirical Distribution

Evaluation

Each of the cases was tested for several AV market penetration scenarios and was compared based on the parking space usage efficiency and Queue Rates.

Simulation Outputs and Inferences

Table 62 Simulation Results Case 1

CASE 1 RESULTS	
Parking Space Results	
Parking Lot Results	

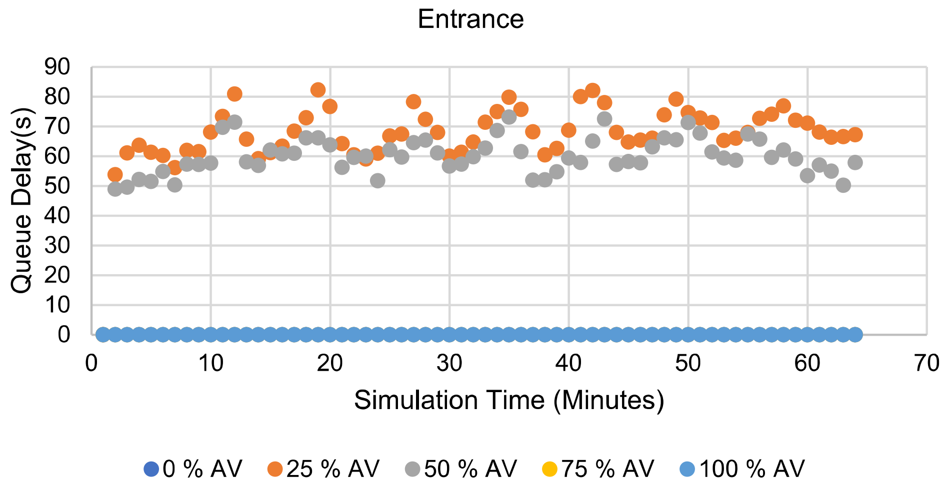
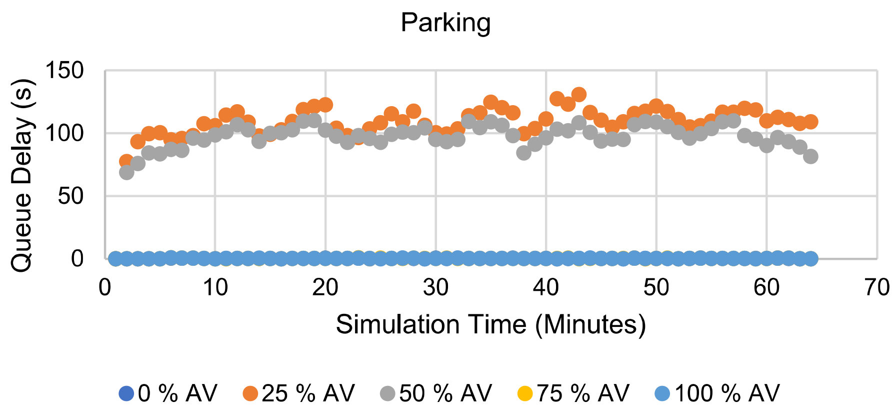
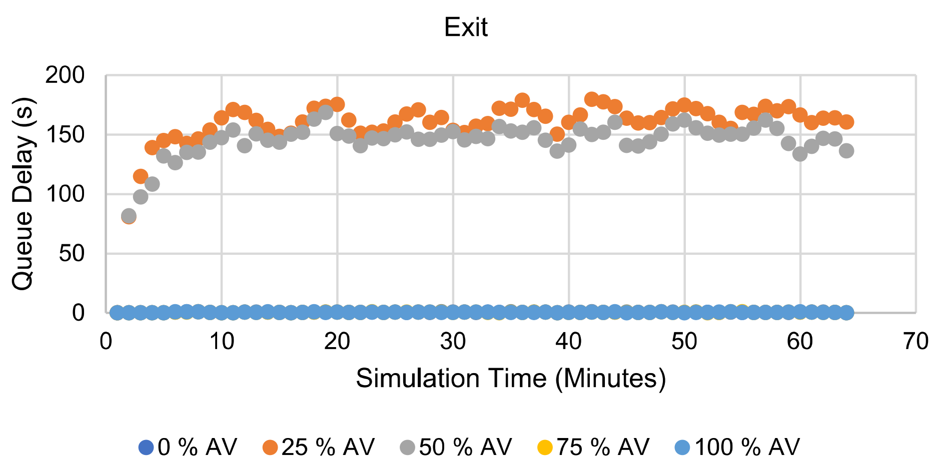
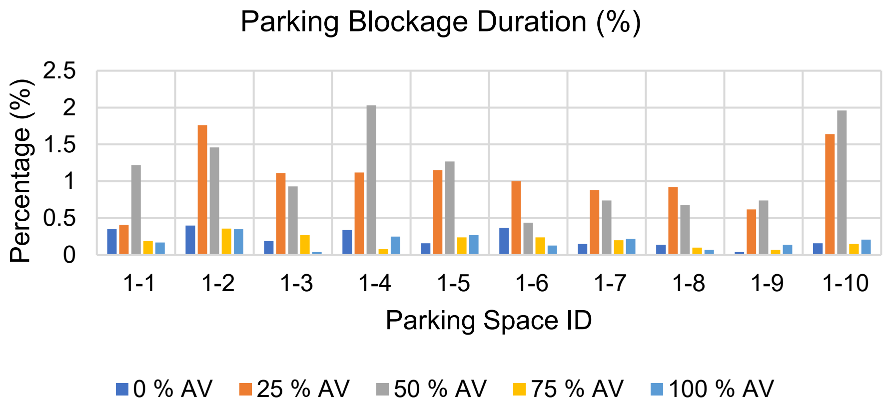
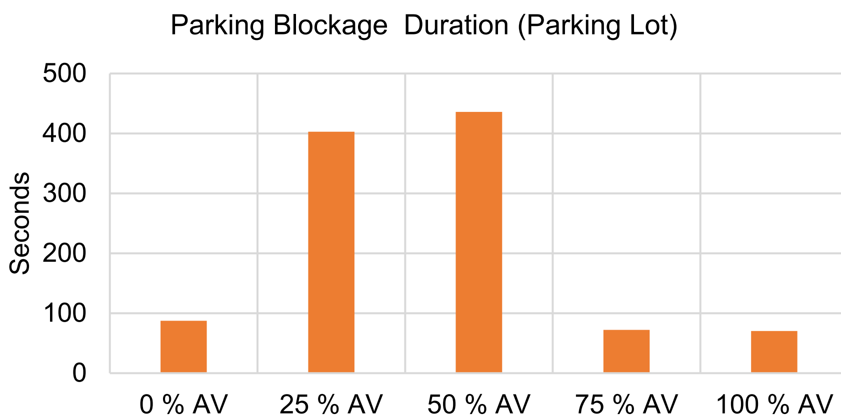
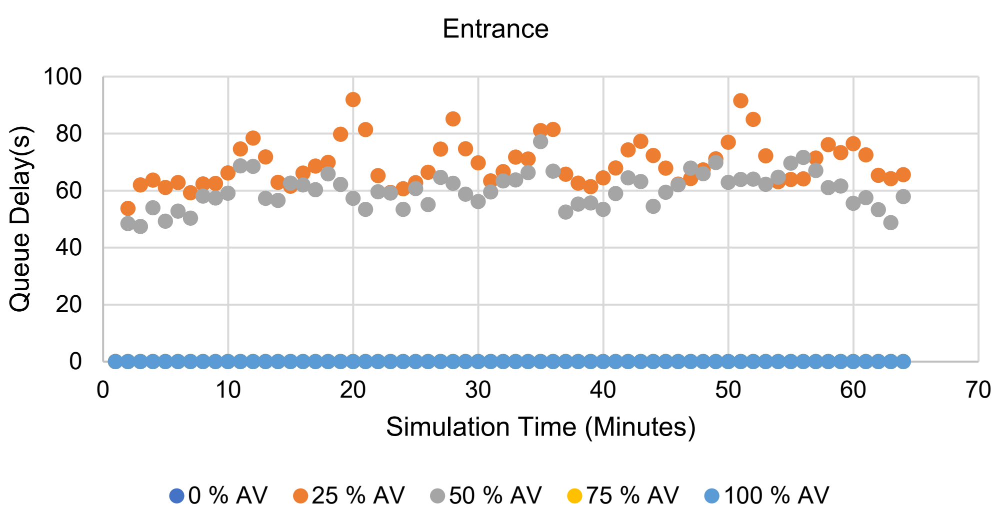
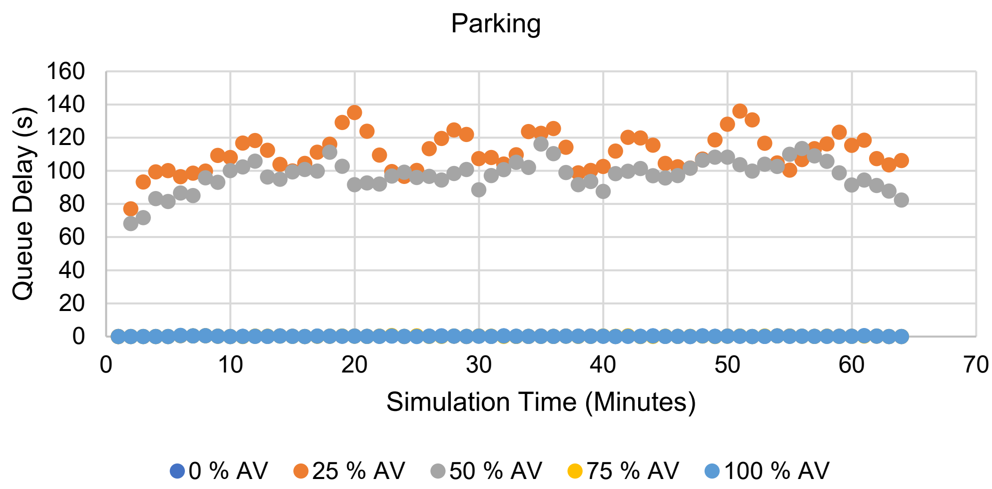
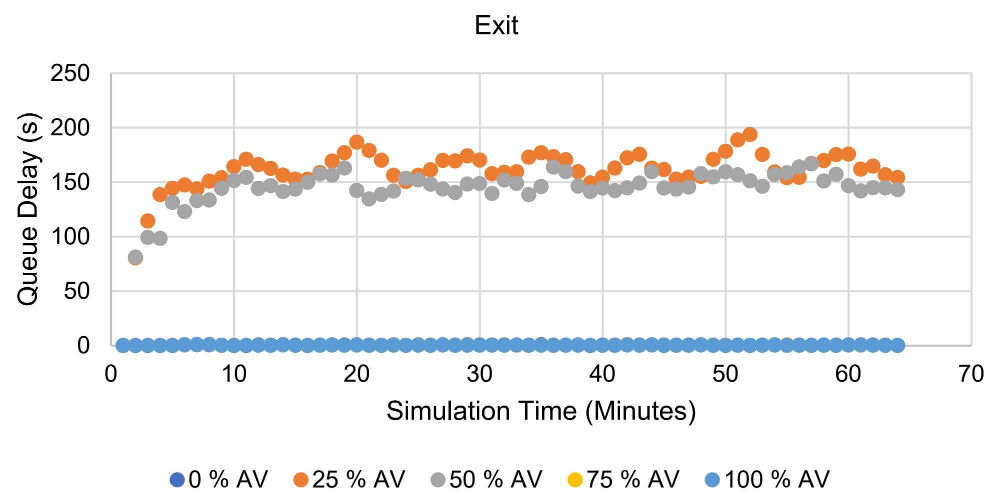
Queue Delay	 Entrance Queue Delay(s) 0 10 20 30 40 50 60 70 80 90 0 10 20 30 40 50 60 70 Simulation Time (Minutes) 0 % AV 25 % AV 50 % AV 75 % AV 100 % AV
	 Parking Queue Delay (s) 0 50 100 150 0 10 20 30 40 50 60 70 Simulation Time (Minutes) 0 % AV 25 % AV 50 % AV 75 % AV 100 % AV
	 Exit Queue Delay (s) 0 50 100 150 200 0 10 20 30 40 50 60 70 Simulation Time (Minutes) 0 % AV 25 % AV 50 % AV 75 % AV 100 % AV

Table 63 Simulation Results Case 2

CASE 2 RESULTS	
Parking Space Results	
Parking Lot Results	
Queue Delay	





User Experience Analysis using Video Data

The ride-hailing service Waymo One™ currently offers autonomous rides in geo-referenced portions of Arizona (see Figure 83). The research team analyzed videos from JJRicks Studios Video Archive(All videos listed on this website are licensed under a Creative Commons Attribution 4.0 International License), containing trip videos from the Arizona Waymo One ride sharing service from the perspective of the passenger (*331*, *337*). Parking lots are unpredictable places where vehicles and people can suddenly appear. They can be challenging to navigate, especially for rookie drivers. The unpredictable nature of pedestrian behavior in a parking lot may call for a quick response from the AV system. It is quite difficult to simulate such situations in a micro-simulation setup. The research team examined videos data frame-by-frame taken from inside the self-driving vehicles to assess the current design to identify shortcomings of the current parking infrastructure and traffic flow inside such facilities and to uncover the latent influence of pedestrian and other non-mortised users on the driving behavior of AVs to resolve this issue. The effectiveness of pickup/drop-off varies significantly depending on the land use, the current parking geometric, and the infrastructural designs, according to video evidence. For instance, one of the shared autonomous ride experience films displayed a lengthy wait at the pickup site at a sizable mall because to the heavy foot traffic entering and leaving the structures. When a self-driving vehicle approaches pedestrians or shoppers, it frequently makes forceful stops to guarantee their safety, which increases the risk of whiplash. This causes discomfort for the passengers inside the AVs, especially during peak hours, it will affect the following vehicles' mobility and safety. Where there is a large variation between the average drop-off and pick-up times, it can be desirable to separate the pickup and drop-off locations. For example, in the case of land use for shopping centers (malls, major grocery stores like Walmart, H.E.B, etc.), customers arriving after engaging in shopping activities need more time and space to load their purchases. The trip route still involves passing through the main building entrances of the shopping area (see Figure 84 and Figure 85), which is a naturally occurring area of walking mode aggregation, prompting the AV to drive more cautiously to ensure their safety. As a result, the vehicle had to stop and wait for a significant amount of time to find a "safe" window to exit the zone.

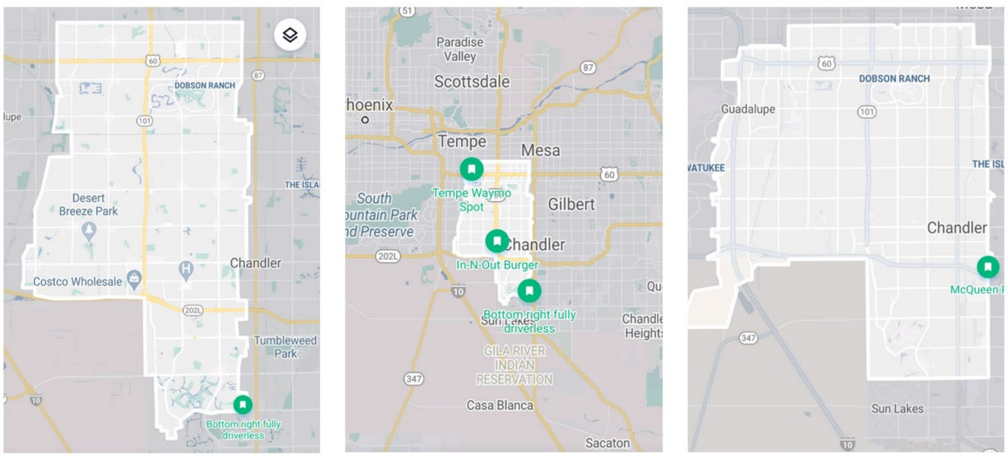


Figure 83 Waymo One Past/Present Operational Areas in Arizona, Source: Waymo One

Figure 84 Shopping Area Behavior - Pedestrian-AV Interaction, Source: JJricks Studios

Figure 85 Pick-up drop location problems, Source: JJricks Studios

Additional Literature Review and Information Search

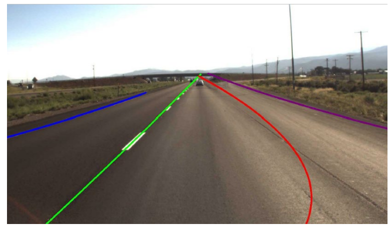
It is essential that road markings and signage are kept up to date because, currently almost all AV technologies depend on them to navigate through their surroundings. Road markers that are significantly damaged or used in an odd way may mislead AVs or potentially cause an accident. Although the issue of road markings may become less important as vehicles use other types of digital infrastructure and mapping for localization and navigation, advanced driver assistance systems (ADAS) already rely on them, and at least some highly automated systems are expected to do so for some time. Lane markings and curb markings are essential for self-driving vehicles since they inform the vehicle about the path and where it should park. This information is used by the vehicle's computer to navigate the path and avoid dangers. Additionally, physical signs will still be required as part of the road infrastructure until such time as manually driven vehicles are removed from the road network or until such time as all manually driven vehicles have some sort of in-vehicle signage display. It may be necessary to increase street lighting, either by greater illumination or more sparsely distributed lights, to ensure that road markings, signals, and signs are visible enough for AVs to operate properly. Leading AV industry experts have noted how poorly maintained lane markers impede the safe and efficient deployment of AVs. The Utah Department of Transportation (UDOT) teamed up with VSI Labs in August 2021 to undertake an AV readiness study of a few Utah routes to get those roads ready for AVs to operate on them. The research team assessed how well Utah roadways worked with AV technologies, particularly the component called Lane-Keep Assist (LKA) that is found in many ADAS. Lanes are evaluated by cameras for LKA and other ADAS systems. Two vehicles were used for the investigation, each of which was outfitted with a full complement of automated driving sensors, including cutting-edge cameras, lidar, radar, and positioning systems. For gathering data from the automation sensors, the vehicles were driven on various sections of road across the state (*338*). Figure 86 depicts AVs machine vision and lane marking detection situations and potential recommendations. Such discrepancies in lane marking could negatively affect traffic safety and flow because parking is still a driving task. Additionally, it could significantly increase the safety of other smaller objects like pedestrians, non-motorized vehicles, motorcycles, and others who are driving close to AVs.

Situation: Long cross-sectional gap- could lead to inadvertent move
Recommendation: Dashed Marker

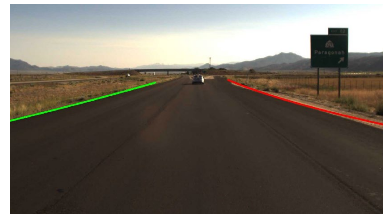
Situation: Surface change- tough contrast
Recommendation: Enhanced marker or ADS not advised in this area

Situation: Heavy shadows cause Lane Keeping Assistance

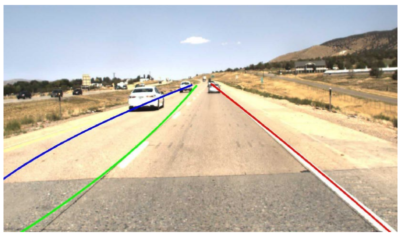
Situation: Poor centerline – cannot detect for some frames
Recommendation: New centerline



Situation: No dashed line
Recommendation: Add dashed line



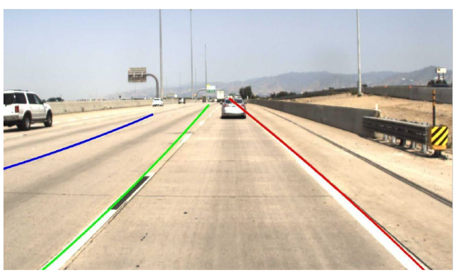
Situation: No markings
Recommendation: Add markings



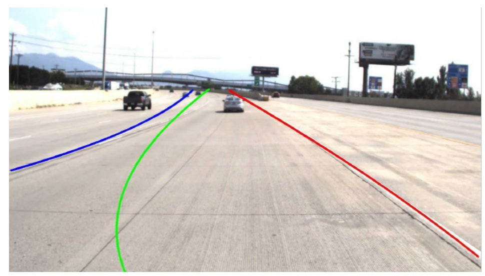
Situation: Surface change, declining contrast leads to some misdetection
Recommendation: High contrast markers

Situation: Poor markings
Recommendation: High contrast markers

Situation: High contrast markers
Recommendation: Tiger tail (Very effective)



Situation: Contrast Markings end, and machine vision loses sight
Recommendation: High contrast markers



Situation: Double Lane offramp leaves a wide gap, machine loses sight
Recommendation: Markers

Figure 86 AV Road Readiness Study Finds – Lane Markings, Source: VSI Lab

Parking Recommendations

The status quo is not an option regarding AV parking. Local planners, engineers and policymakers need to take a different approach when it comes to the capital expenditures for parking facilities, particularly those that include long-term debt and bond issuance. Adopting less than preparations can be better than taking on the longer-term risk of stranded parking assets. It is recommended that medium- to long-term planning activities consider different impacts of AVs. These activities include: updating transport models with new assumptions, forecasting financial revenues, designating traffic lanes for simultaneous operation of AVs and/or conventional automobiles, updating traffic signs and markings; reducing lane widths, adjusting speed limits, traffic signal locations and timing, eliminating or reducing parking spaces and adding more drop off/pick up locations, reclaiming city center surface parking lots for potential future developments, reclaiming right-of-way for people and other modes of transport, doubling the use of suburb on-street parking areas as charging stations, and developing new predictive models for pavement maintenance (*339*). Planners and transportation engineers must also start thinking differently about parking requirements and building design. For instance, six parking places may not be required for every

1,000 square feet of shop space. Instead, additional pick-up/drop-off facilities with appropriate infrastructures can be integrated. On the residential side, dwelling/resident units might no longer require garages, which might reduce the cost of building new homes or increase the size of living space in existing residential zones. There is no doubt that the parking industry will be gradually but significantly affected by the increasing development of AV technology.

- The AV reclaimed area that is being used for pickup and drop-off will require some type of shelter to protect users from the weather. Shelters should be installed at the main passenger-loading locations to safeguard transport users. Such shelters ought to be large enough to hold off-peak passenger volumes at the very least. The number of passengers the shelter is expected to accommodate should be multiplied by a factor of 3 to 5 ft^2 [0.3 to 0.5 m^2] to establish the shelter's size. It is not necessary to build a shelter that can hold all passengers at the time of building because the shelter can be expanded reasonably quickly afterwards if enough platform space is built originally. Lighting, benches, route information, garbage cans, and occasionally telephones are extras that need to be included with the shelter.
- Parking over the line/space-how does AV considered such spaces (for instance, large personal pickup trucks, Vans etc. (see illustration in Figure 87 and Figure 88).This situation could also be triggered by poor detection by the vehicle sensors. Weather and Visibility will be a big deciding factor on this specific effect.
- For parallel parking, in several places, a vehicle must be parked within 30 to 45 cm from the curb (curb clearance). If the AV sensors are not accurate enough, the result could be a vehicle that is parked much too far from the curb or, conversely, runs over it.
-

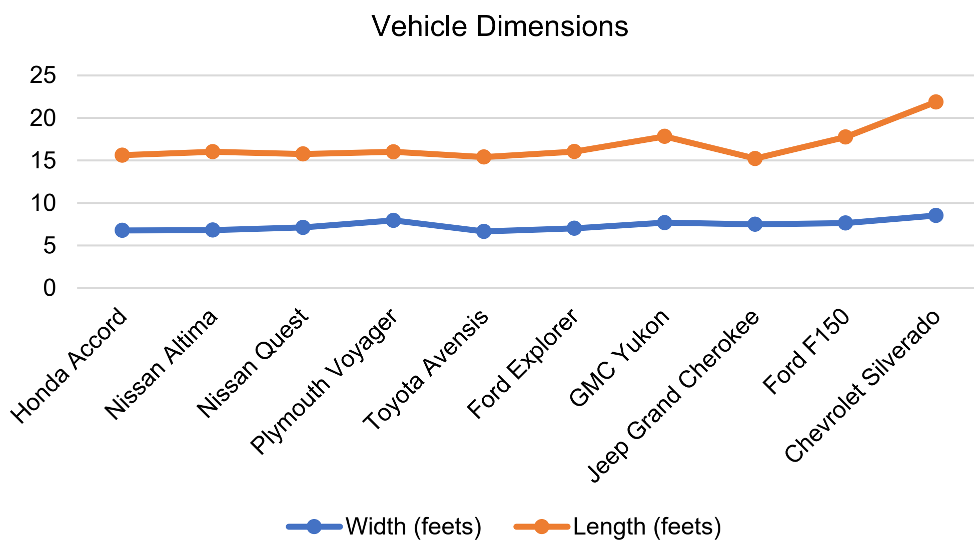


Figure 87 General Vehicle Dimension, Source: PTV VISSIM

Figure 88 Parking Over the Space/Markings, Source: Google Images

Parking Spot Delineations and Marking: Parking spot stoppers and pavement marking that are the right color and contrast can help AV sensors do parking maneuvers more safely and efficiently (*340*) (See Figure 89 and Figure 90). Figure 89 depicts AV friendly lane markings on urban streets clearly delineating the on street parallel parking with designated loading zones/pick-up drop off areas (lateral yellow lines), bike lanes and travel lanes.

Figure 89 Parking Spot Stopper, Source Leddartech

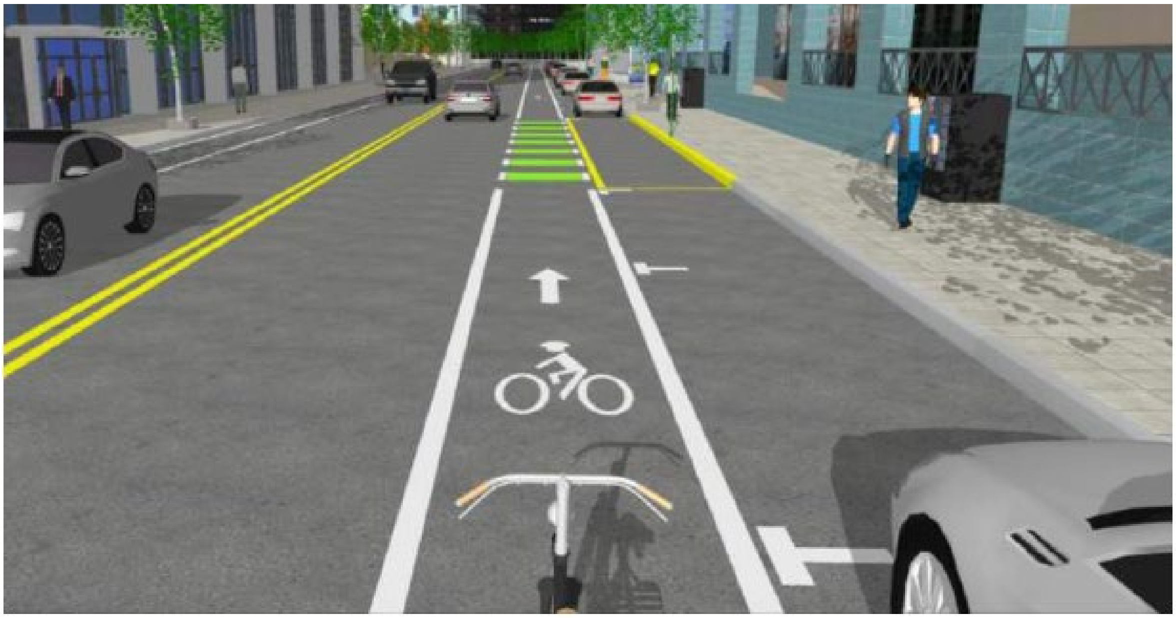


Figure 90 Pavement Marking on streets, Source: Hurwitzet al. (*341*)

- Zoning the TAZs based on the pedestrian and other non-motorized activities
- Pick-up drop off: number/dimension/position/infrastructure/markings
- It is advised to use traffic markings to designate the parking lane on streets with an asphalt surface. Where parking turnover occurs, the labeling of parking places encourages more orderly and efficient usage of those spaces, which helps to reduce encroachment on areas such as fire hydrant zones, bus stops, loading zones, and approaches to corners.
- Due to the ability for automobiles to navigate themselves to more remote storage facilities, many on-street parking spaces may vanish. Some commuters choose to use company vehicles, carpool, take public transportation, ride motorcycles or bicycles, or walk. Designers thus will be able to dispense with some of the features of today's roadways. They will also need to introduce new ones, such as massively expanded drop- off areas. As roads become narrower, less urban surface may remain paved, thereby reducing water runoff.
- Off-street parking traffic rules and law enforcement needs to be addressed
- The roadways of the future can be constructed very differently from the highways of today if vehicles are autonomous and on-street parking is not required. Lanes can be made narrower since autonomous vehicles cannot veer or wobble because of distracted driving. For AV-segregated infrastructure with proper communication infrastructure, clear signage, and lane marking, narrowing lane width is practical. If the road infrastructure is shared with conventional vehicles, subjective (stochastic) human driving behavior has a substantial impact on safety.
- A parking lane that is close to an intersection needs to be handled carefully. Design of such facilities/infrastructure may need to be revised to consider AV and the corresponding safety features/thresholds or even disengagements that could negatively affect the traffic behind them or, in the worst-case scenario, the entire intersection. If the lane is extended to the intersection, right-turning vehicles may utilize it even if there are no parked vehicles there, which could result in undesired operations. The effective corner radius for large right-turning vehicles, however, can be increased by maintaining a parking lane. Other alternatives include

restricting parking close to the crossing or using a transition between parking lanes (as shown in Figure 91)

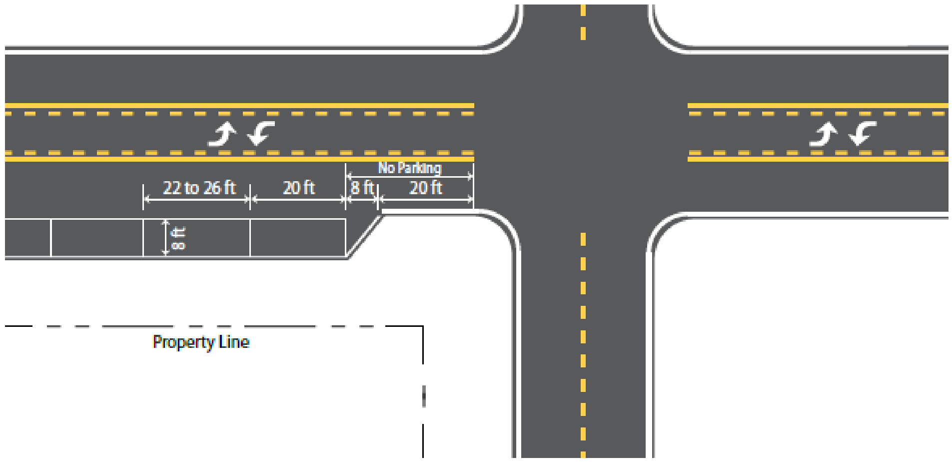


Figure 91 Parking Lane Transition at Intersection Adapted from AASHTO, 2011

Paired Parking on streets: When considering the safety headway of AV and unplanned disengagements, paired parking with sufficient spacing may be advantageous. In the worst-case scenario, AV can use these locations to reengage the driving mode manually or remotely (see Figure 92)

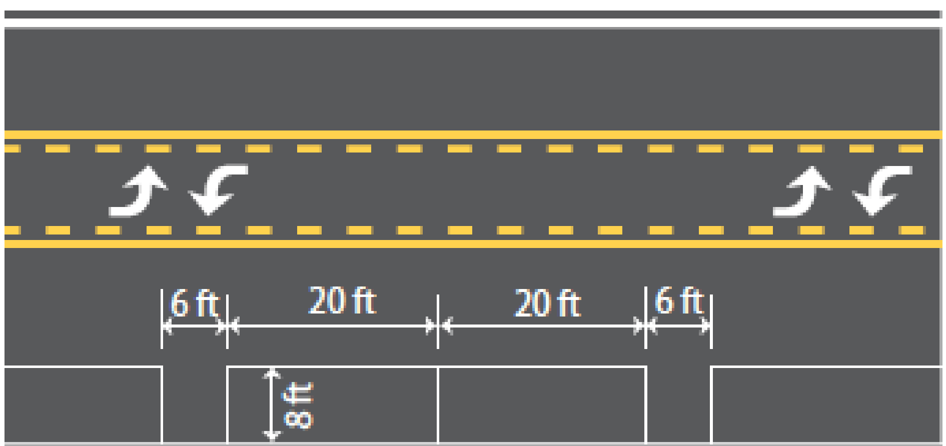


Figure 92 Paired Parking, Adapted from AASHTO, 2011

- Parkofon (*342*) is gathering information about parking from the perspective of the motorist to glean important and crucial details like where people park, when they park, and how long they stay there. Determining how autonomous and non-autonomous vehicles can share parking spaces in the future depends on such datasets. Parking data from many different sources is needed as the market shifts to autonomous vehicles. More Behavioral Models to be tested to understand the interactions between ADAS systems of Avs with the static and dynamics entities on the road network will critical information for the design of cross-sectional elements of Urban streets with high pedestrian activity.
- Most modern vehicles currently utilize cameras and radar as standard sensors for sophisticated driving assistance and park assist. Lower levels of autonomy are also possible when a human oversees the system. However, lidar, a sensor that detects distances by

pulsing lasers, has shown to be immensely valuable for fully autonomous vehicles. Lidar enables self-driving vehicles to see their surroundings in three dimensions. It gives the road topography, as well as the nearby vehicles and people, shape, and depth. Additionally, it performs equally as well in low-light situations as radar does. Lidar sensors can create a precise 3D image from the signals that instantly reflect by rapidly generating invisible lasers (see illustration shown in Figure 93. To increase safety and diversity of sensor data, these signals produce "point clouds" that depict the environment surrounding the vehicle (*343*). Mapping (digitizing) will be essential for smooth operation of AV without interruptions or disengagements. Places without maps coverage needs to integrate with proper communications channels to communicate and direct the AV, especially to parking garages, off street parking zones, etc.

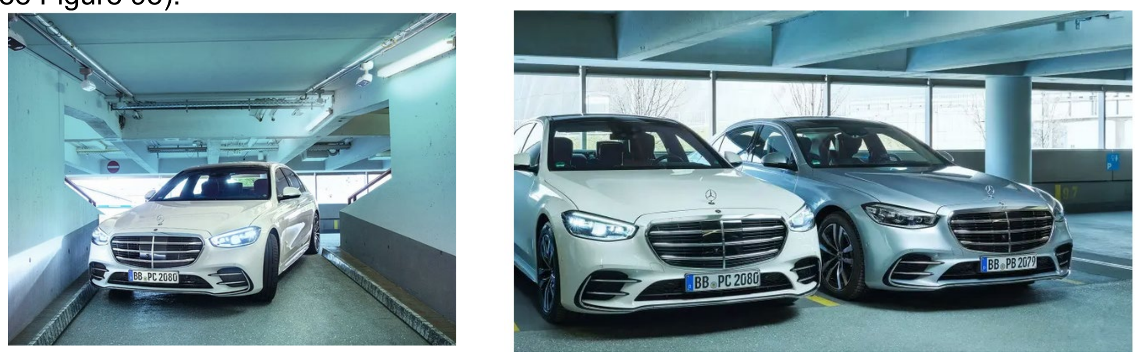
Figure 93 Visualization of a Nvidia- Velodyne lidar sensor detecting objects with laser pulses Source: Nvidia

- Research on parking usage is being done by the Downtown Austin Alliance and Nelson Nygaard (*344*) proposing for a better parking management system supported by new enforcement, regulation, and pricing policies will be developed because of this initiative. But using technology to cut down on the number of kilometers driven by vehicles to find parking will be just as significant:
    - Apps that make it possible to find and reserve parking spaces in real-time
    - Digital navigation signs that communicate parking availability to vehicles and are highly visible
- As the usage patterns of downtown streets change, there will need to be considerable modifications to urban parking regulations. Many cities require a minimum number of parking spaces for structures in the downtown area, especially those that are strongly dependent on the automobile. They appear to be arguing that most people who live, work, and shop in these cities commute in single-occupant vehicles and trucks and so need a nearby parking space to avoid clogging up the downtown traffic. These habits will alter because of the AV revolution, and parking regulations will need to adjust to reflect this.

Innovative Off-Parking Solutions

Automated and Semi-Automated Parking Lots

Automation in parking lots has increased worldwide as an effective way to improve efficiency in parking. The process involves automated machinery to park the vehicle. When a vehicle enters the parking lot, it is scanned by lasers before being elevated and transferred by a moving to a parking space. This system is like an automated storage bracket and can accommodate four times as many vehicles as a conventional parking facility. The effective use of space is because the drivers exit the vehicle before it is parked, eliminating the need to leave many spaces between the vehicles. With automated parking systems, parking lots will become much smaller, or there will be less need for more parking lots as the available ones will be enough for the vehicles (see Figure 94). Parking lots will take up more vertical space than horizontal space because machines park the vehicles rather than drivers. Other way such parking center can improve the net system parking efficiency is via communication channels whereby, a control center and vehicles can cooperate in parking lots to make things more efficient. For example, when a vehicle enters the parking lot, the driver gets out and the control center can distribute a map of the parking lot to the vehicle. The control center can also instruct the vehicle on a driving route, speed, and parking position before the vehicle leaves the parking lot. This results in high-density parking by eliminating ramps and turning radiuses and by removing humans from inside the parking structure (see Figure 95).



Cameras on walls assisting with the AV manuevering in tight spaces

Parking Space Reduction

Figure 94 Automatic Parking Infrastructure, Source: Bosch

Figure 95 U-tron's fully and semi-automated parking, Source: U-tron (*345*)

The development of autonomous valet parking facilities is complex and requires a significant investment. Parking lots can be difficult for both human drivers and autonomous systems due to the architecture, uncertain environment, and shifting environmental conditions. The recommendations made in this study demonstrate the necessity of utilizing a variety of complementary sensing technologies that can provide redundancy to cover all potential scenarios.

Prior adoption of required technologies in vehicles

- For a policy of pre-equipping automobiles, the prior dissemination of advanced driver assistance and remote parking features on highways and other roadways is regarded as a prerequisite for technologies that support autonomous valet parking. Autonomous parking will begin once parking lots equipped with the necessary equipment and signages are ready in the future. These technologies will be used to control the steering, braking, axel, and switchover from going forward to going in reverse, as well as vehicle remote control.
- Fully automatic parking in exclusive parking lots with well-developed infrastructure could be considered initially. The use of fully automatic parking functions is expected to be sequentially expanded to general parking lots. The expected benefits of autonomous valet parking at specially equipped parking lots tabulated below (see Table 64).

Table 64 Features of autonomous valet parking at specially equipped parking lots

Fewer accidents	With specially equipped parking there would be no ordinary vehicles or pedestrians to deal with. This would lead to a very low possibility of collisions with pedestrians or infrastructure.
Effective use of space	every space for parking and getting in and out of vehicles should have a width of 2.5 m for ordinary vehicles, or a width of 3.5 m for vehicles of the disabled, in contrast with actual vehicle widths (4.8 ft. for mini vehicles, 1.7 m for midsize vehicles, and 1.88 m for full-sized vehicles). Autonomous valet parking would allow the parking lot to have an optimized layout. In other words, it enables effective use of space by making the space between vehicles narrow and saving pedestrian passage space, among other applications.
Easing congestion	Autonomous valet parking would eliminate the movement of vehicles looking for parking space. This would substantially ease congestion in parking lots.
Reservation service	Parking lot equipment manufacturers can readily install a parking space reservation service for autonomous valet parking-compatible vehicles.

Summary

Several current planning agencies' priorities include providing good accessibility, addressing transportation equity issues, reducing greenhouse gas (GHG) emissions, reducing traffic and travel time, reducing the cost of travel, creating more public space, creating open /green spaces, improving safety, and making our communities healthier and more livable. AVs have the potential to make significant progress in all these areas. However, without good planning and in the absence of competent legislation, AV technology might also make communities less habitable, increase GHG emissions, lead suburbs to spread farther apart, and worsen inequality. Inadequate planning will influence the effectiveness of the transportation system as well as the land use or activity system, economic welfare, human health, livability of cities, environmental sustainability, and other areas. Cities are now in a phase of transition and uncertainty because of the development of AV technologies. This period involves balancing the existing legal framework with the new problems that the technology raises. Lane departure warning systems, which warn drivers when they veer outside of their lane, and adaptive cruise control, which maintains a vehicle's speed and the following distance between a vehicle and the vehicle in front of it, are just two automated features that are already being built into and sold with vehicles. Technically, using only devices on the vehicle side to provide safety in conventional parking spaces is challenging. Therefore, in order to reduce the strain on both vehicles and parking facilities, decision-makers and planners must first create parking lots specifically for fully automatic parking (a designated area that is exclusive to fully automatic parking and is separated from other traffic, such as pedestrians and general vehicles, and has monitoring devices installed inside the parking lots and control center), as well as ensure safety through cooperation between the vehicles and control center in the parking lots (*346*, *347*). Several of these scenario and recommendations suggest a need for the segregation of AVs and from non-AV traffic. Considering the expense of building such structures and the limited availability of land, separated infrastructure schemes dependent on fully segregated infrastructure may be difficult especially in congested urban area. Being relatively new, the self-driving vehicle industry and technology make it difficult to predict all the changes that will take place as they mature. Owners of parking assets would be advised to keep an eye on the following developments as a result (*348*):

- If autonomous vehicles become widely accepted by consumers, it is likely that there will be a shift from single-passenger, single-stop journeys to multi-user, multi-stop journeys. This could have a significant impact on commercial parking facilities, which would see a decrease in monthly parking revenue and an increase in transient revenue.
- Transportation service providers like Lyft and Uber need to have reserved parking spaces for waiting and maintenance areas for their vehicles like how non-autonomous car-sharing services like Zipcar work. If parking asset owners can successfully negotiate this, it could provide a reliable and long-term source of income.
- The Shared Mobility Principles for Livable Cities, as codified by a coalition of shared transportation companies and other NGOs, distinctly states that AVs in urban centers should only be operated by well-regulated shared fleets. If local decision-makers weave this principle into policy making, consumers that wish to commute via AV would be unable to bring their own, potentially having a negative impact on parking demand. However, if they decide against AVs being operated exclusively in fleets, more people could be commuting to work by vehicle than we do today. It is significantly more comfortable and convenient to be driven to work in a private vehicle than to take public transit, and if AVs are ubiquitous and operating perfectly, congestion will be minimal. Thus, demand for parking will increase.
- Fleet management service for autonomous vehicles will be needed. These vehicles will need to be refueled and/or recharged. They will need to have their interiors cleaned. They will need to have their sensors calibrated and cleaned. They will need to be repaired and maintained.
- Parking spaces for non-autonomous vehicles may be challenging for autonomous vehicles. This could be advantageous for parking garages with attendants, who can assist in parking and stacking automobiles to enhance capacity. Additionally, commercial AV businesses may require strategically placed maintenance stations, which could be positioned in parking facilities.

CHAPTER 8: CONCLUSION AND RECOMMENDATIONS

Following findings were observed from the current study and it has been summarized below:

Pavement Markings

- Uniformity, design, and maintenance of markings are crucial for machine vision.
- Majority of the states are moving towards 6-inch wide marking as mentioned earlier in the findings section.
- Markings must be contrasting enough with surroundings and an evaluation criterion is to be developed.
- As observed in NCHRP 20-102 (6), markings must have sufficient levels of luminance and retro-reflectivity both under day and nighttime conditions.
- It is recommended to have minimum performance criteria established for markings based on machine vision for different functional classes that have different speed limits.

TSRS

- Timely maintenance of traffic signs: Routine maintenance of traffic signs should be done. The sensors used by AVs can provide additional information regarding signs that needs maintenance.
- Implementing strict rules and policies against vandalism.
- Prefer retroreflective signs over illuminated signs. However, if illuminated signs are used, standardize the flicker/refresh rate of the electronic signs.
- Further study needs to be done regarding placement of traffic signs on both sides of the roadway.

Classification of Roadways

- Consensus has not been reached among the AV community to classify the roadway system based on the AV readiness index. Many believe that it can be a futuristic approach.
- Rather focus should be on the infrastructure readiness index, such as striping, signage, pavement, etc. that are deemed beneficial for both human drivers and AVs.

Digital Maps

- At the early stages of ADS deployment, there is a high tendency among the AV industry to use digital maps. Therefore, these digital maps are currently developed independently by each AV firm. This leads to redundancy among the system and could be solved by having a unique platform that shall develop and maintain the digitized network.
- It would be preferable for the IOOs to develop the digital network and assume the responsibility for its maintenance. This would exceptionally benefit in providing real-time information to the vehicles under traffic incidents, planned construction activities, traffic redirections, etc. However, it is also dependent on numerous other factors that needs further investigation.
- In the absence of a single platform that maintains the digital maps, there is a need for updating these maps periodically which can be achieved using roadside units.
- V2V and V2I communication can solve the problem of providing real-time information to the vehicles.

- Current technology requires both digital maps and machine vision to operate in the real world, therefore both need to work in conjunction.

Urban Conditions

Lane Reductions

- For machine vision, it is recommended to have appropriate signages with standardized transitional pavement markings.
- Having a supplemental plaque that conveys the distance at which reduction in lane takes place can be useful.
- HD maps can provide accurate information about such challenges throughout the ODD.

Intersections

- Highly recommended to have dotted lane line extensions through the intersections that have more than one turning lane.
- Recommended to have dotted extension before the start of turning lanes (right or left) to ensure continuity in markings as shown in Figure 10.
- V2V connectivity and V2I connectivity can improve the ability of AVs at unprotected left turns.

Stop Controlled Junctions

- A clear line of sight without any obstruction at stop-controlled T-junctions.
- Prolific usage of supplemental plaques wherever necessary to disseminate relevant information.
- V2V and V2I connectivity can provide exhaustive information on driver's behavior at intersections.

Freeways

- Recommended to have dotted line extensions for entrance ramps.
- Similarly dotted line extensions along the exit ramps are even more critical.
- Markings in the chevron area must be standardized either by painting entirely solid or by using chevron markings. Further research is needed on the type of markings at this place.
- Information about width of shoulders is to be maintained and communicated with AV organizations in the event of disengagement. Further the necessity to increase the width of shoulders is worth investigating.
- Practice of covering signages with black cloth material can still be continued.
- Too many traffic signs that can cause confusion to AVs is not usually desired.

Work Zones

- The use of standardized work zone data (USDOT's work zone data exchange data) is encouraged.
- Use of radar reflective vests and retroreflective work zone signs to help the movement of AVs in adverse weather and bad lighting.
- The placement and spacing of vertical devices in the work zone should be standardized.
- V2V and V2I communication can play a vital role in the coming years.
- Further research is needed to determine the tradeoff of increasing number of sensors in an AV and safety concerns of aggressive AV driving behaviors.

- Further research and study should be done regarding the use of orange pavement markings in work zones.

Traffic Signals

- Having consistency in traffic signal head positioning is not of paramount importance. However, while constructing new infrastructure maintaining consistency will be beneficial.
- HD maps will play a crucial role in helping AVs navigate through a signalized intersection.
- CV technology with SPaT/Map messaging is critical to an automated future: E.g., the line of sight of a smaller AV vehicle is blocked by heavy freight and the AV that works on machine vision cannot perceive the traffic signal. In this case, SPaT messaging can play a significantly important role.
- A dedicated signal head per lane should be provided in critical locations.
- The stock dataset available to train AVs to navigate a TLC intersection is not enough. There should be data sharing among various AV companies. Moreover, the AV developers should focus on improving the machine learning and computer vision systems to detect traffic signals under all weather and lighting conditions.
- Traffic signals should be contrast enough with its surroundings and must be visible under all light and weather conditions (such as under direct sunlight, fog, rain, etc.).

Active Modes

- In a mixed environment, responses suggested coloring the pavement wherever there is high movement of non-motorized traffic. Although TxDOT currently does not use colored bike lanes it may be useful for AVs in some areas such ae university campuses, schools, and parks. Alternatives to colored bike lane such as highly contrast marking may serve the purpose, however it needs to be evaluated.
- Gaining the trust of pedestrians and bicyclists is a major step forward in the deployment of AVs. In the early stages, providing a segregated bike lane, wherever possible, in high-density areas having a multimodal transportation system is recommended.
- In areas where there is limited ROW and high bicycle movements, speed regulatory techniques can be explored.

Others: Disengagement in AVs and Roadside Barriers

Disengagements in AVs

- Data sharing between different AV developers, IOOs, and OEMs are encouraged because it will expedite the AV deployment process. E.g.: a map where every car company shares information regarding where, why, and how their vehicles disengaged so that it can be prevented by other companies.
- Advanced simulation techniques similar to that adopted by the aerospace industry should be done.
- The disengagements should be categorized and classified. In doing so, it will help in targeted interventions.
- Various and routine public education events should be organized to inform and educate people about AVs.

Roadside Barriers

- Use retroreflective striping and painting in concrete barriers to distinguish them and improve visibility in all weather conditions.
- Set a standard for minimum contrast requirements for roadside barriers.
- Consider avoiding roadside barriers that are low in height to enhance their detectability by the machine vision.
- Proper and timely maintenance of vegetation growing on the roadside.
- The AV developers should be encouraged to develop more robust AI techniques and training algorithms to detect roadside barriers in all weather conditions.

Parking Challengers and Solutions

Vehicles provide many people with a combination of speed, autonomy, and privacy that is unrivaled by any other mode of transportation. However, the reality is that most private vehicles spend most of their time parked, taking up valuable space that could be used for other purposes.

As parking concerns continue to grow in cities and urban regions, advances in parking technology are being made to accommodate the transition to self-driving vehicles. This transition will most likely take some time and involve a mix of both human-driven and Autonomous Vehicles (AV).

Some parking space will be freed up by more efficient driving patterns, but what will really make a difference is integrating AVs with vehicle sharing and innovative techniques for parking and maintaining automobiles.

This study provides a summary of the design considerations and recommendations considering mixed traffic scenarios. The research team used microsimulation tools (PTV Vissim), video analysis of user experiences, and focused information search to more precisely summarize the essential design criteria that needs modification and summarize additional new attributes that designers, engineers, planners, or current or potential parking landowners should take into consideration while retrofitting or redesigning existing parking infrastructure.

To comprehend the effects of AV on street parking under various market penetration scenarios, micro-simulation analyses were carried out, specifically examining the cross-sectional width requirements for parking lanes and traffic lanes. The simulation analyses were complimented by video data analysis and targeted information search specifically to understand the influence of the external factors to be considered while designing for future parking facilities and infrastructure for AVs.

Some communities are already making minor adjustments in this area, such as reducing the amount of parking restrictions, improving public transit, or freeing up land for development. However, modern technology might take this much further. Ride-sharing firms like Uber and Lyft already allude to a future in which automobiles are used more effectively and collectively occupy less space. And in theory, cities might significantly reduce their transportation footprint if self-driving vehicles proliferate.

To appropriately channel AV traffic and avoid what may be a series of traffic bottlenecks, particularly during rush hours as people go to and from work and school, new land-use regulations and traffic laws will need to be developed.

The study used three different forms of analysis to determine how AVs might affect the parking designs that were already in place. All the vehicles on the road could fit into far less space if they were all autonomous. AV might go closer together without worrying about colliding with one another in the rear. The vehicles themselves may be smaller and thinner, occupying less space, if collisions decreased in frequency.

With little to no impact on travel times, city planners could narrow roadways or even reduce the number of lanes. Lanes designated for autonomous vehicles will not need to be wider to account for human error. If vehicle dimensions essentially remain constant, lane width could be reduced by up to 20%, for a width of about eight feet, to be closer to real vehicle width. Because they deter unsafe driving behavior and reduce vehicle speeds, decreases of even ten feet in the space between conventional vehicles, pedestrians, and bicyclists could be advantageous in circumstances with mixed traffic.

The increased performance of AVs makes the case for implementing road diets in some places stronger. This is because the number of lanes and their width can be decreased. In the long run, medians might be shortened or abolished since opposing-direction traffic may no longer require a safety buffer.

Past research has shown that the capacity of freeways will roughly double when all vehicles are fully automated. Although we might not anticipate the same outcomes on surface streets, the idea still holds true. This opens the door to the building of numerous other "road diets," where the city may cut back on the number of driving lanes for automobiles and utilize the space for other uses. Even while road diets can promote safety and support both motorized and nonmotorized transit modes along a corridor, they may not be appropriate or viable in all locations. For example, in many metropolitan settings, they may cause issues with levels of service and capacity.

Lane markings and curb markings are critical for AVs because they provide the vehicle with information about the path it should follow and where it should park. These markings are used by the AV's computer system to navigate the road and avoid hazards. While physical signs will still be necessary until all manually driven vehicles have some form of in-vehicle signage display or are removed from the road network, it may be necessary to improve street lighting to ensure that these markings, signals, and signs are visible enough for AVs to operate safely and efficiently.

In addition to lane markings and curb markings, it will also be important to consider other infrastructure elements such as dedicated lanes for pick-up and drop-off, charging stations, and improved wayfinding and signage to support the deployment of AVs in the future.

In conclusion, the future of parking design for autonomous cars presents both challenges and opportunities. As autonomous vehicles become more prevalent, it will be important for parking facilities to adapt and provide infrastructure that supports these vehicles. This may include features such as dedicated lanes for pick-up and drop-off, charging stations, and improved wayfinding and signage. By considering the unique needs of autonomous cars, parking designers can create functional and efficient parking solutions that support the transition to a fully autonomous transportation system.

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Appendix 1

This appendix contains all the questions that were discussed in the expert opinion study (video interview or web-based questionnaire). The questionnaire/ question set consisted of 25 questions. Question 13 is further divided into 13, 13 (a), 13(b), and 13(c).

Question 1: In a few lines, please share your views on how AVs operate in the real world.

Question 2: In addition to digitizing the current road infrastructure, according to you what are the most certain aspects that AVs require to operate on our roads?

Note: Digitizing refers to HD maps with high accuracy containing information about signages, markings and more.

Question 3: According to you, what are the current challenges of the traffic sign recognition system and how can they be addressed?

Question 4: What shall be your opinion to have a classified roadway system based on AV readiness index?

Question 5: Do AVs solely rely on machine vision for detecting pavement markings or can the high-definition digital maps provide the accurate details of markings?

Question 6: Many operators report one of the challenges for AVs is to be maneuvering over merge locations, according to you why is this occurring and what can be a solution for it?

Question 7: Can the roadway with lane drops as seen in figure 7 below be a challenge for AV motion, if so, then what can be an ideal solution to address such challenges for AVs?

Figure 7. Source: Kurt Kohlstedt

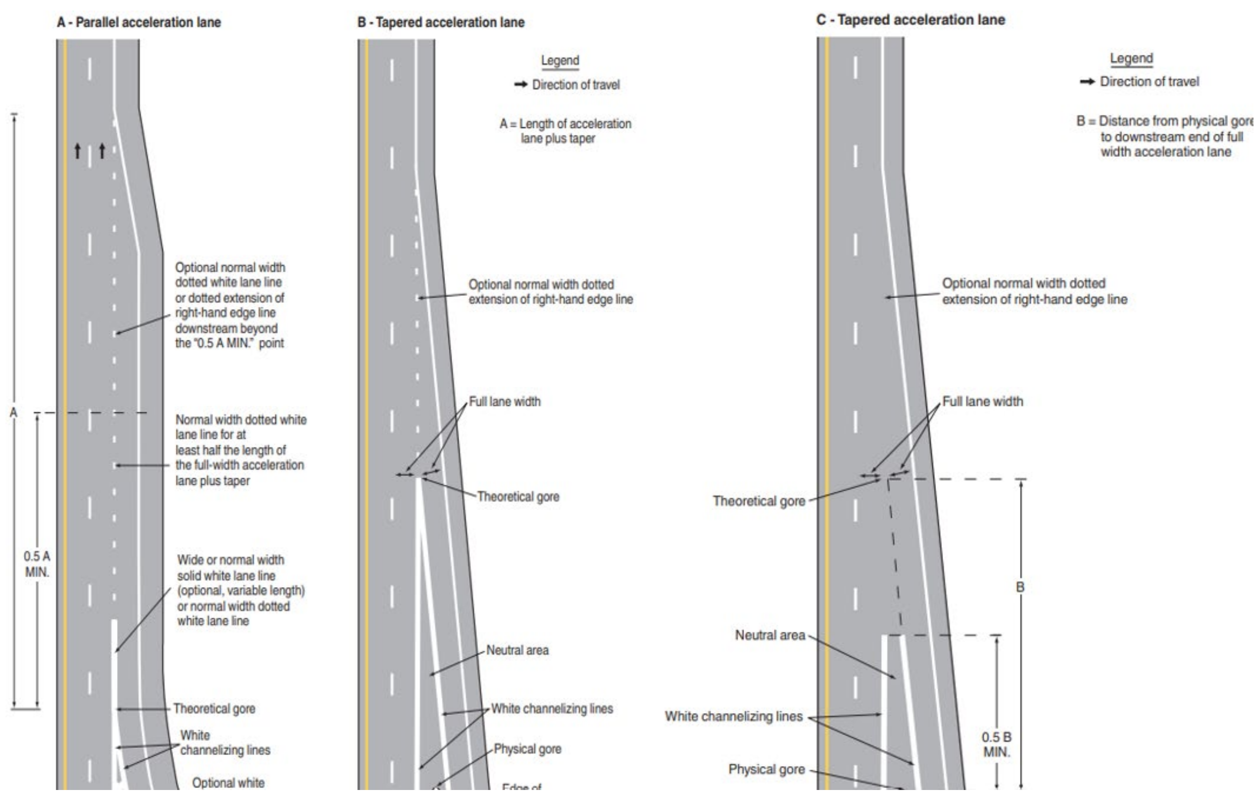
Question 8: For the AVs, how crucial is transition pavement markings for lane drops or sudden increase in lanes on a scale of 1 to 5 (1 being the lowest and 5 being the highest)?

Question 9: As shown in fig 9, How challenging is the zipper merge for AV at construction sites, what can be a suitable solution for AVs to make the zipper merge smoother?

Figure 9. Source: NCSU ITRE

Question 10: Figure 10 provides different types of acceleration lanes, how challenging is it for AVs to maneuver in such a taper area? Since the full lane width continues to taper beyond theoretical gore for tapered acceleration lanes and downstream for parallel acceleration lanes? What can be the solution for AVs in such scenarios?

Figure 10. Source: TMUTCD

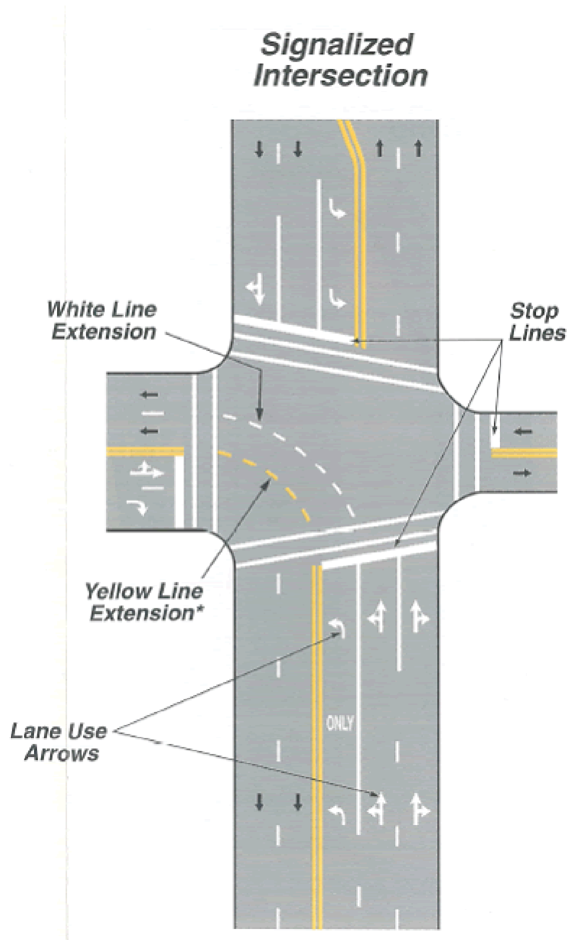


Question 11: A recommendation for question 10 is to extend the dotted lines, would it be sufficient for AVs to safely navigate these regions?

Question 12: At the exit ramps one of the recommended measures is to have extended dotted lines, is having such a measure sufficient, or is there something else you would like to recommend?

Question 13: As given in figure 13 how challenging is the left turning movement for AVs, at signalized intersections, especially with multiple left turning lanes as seen in the figure below. Does the non-conformity of human drivers to stay within their lane during such turnings can pose a challenge to AVs maneuver? If so, can this be mitigated by including line extensions through intersections? In addition, what shall be your recommendations?

Figure 13. Source: FHWA MUTCD



Question 13 (a): In continuation with the above question do you expect any challenges on AVs movement at unprotected left turns? Do you have any recommendations?

Question 13 (b): According to you, do you perceive the gap acceptance of AVs at a stop-controlled junction (such as T junctions) where cross traffic does not stop, to be extremely challenging?

Figure 13 (a). Source: TMUTCD

Question 13 (c): Based on your response to the above question, how likely would you suggest to have an additional sensor upstream on the intersection that can relay the gap information to AVs?

Question 14: Many AV industries report various discrepancies happening to a large extent " planning discrepancy: resulting in incorrect trajectory estimation" or "perception discrepancy: failed to detect the object correctly", although it this seem to lessen with increase in trial runs, are there any fundamental measures that is required to prevent such discrepancies?

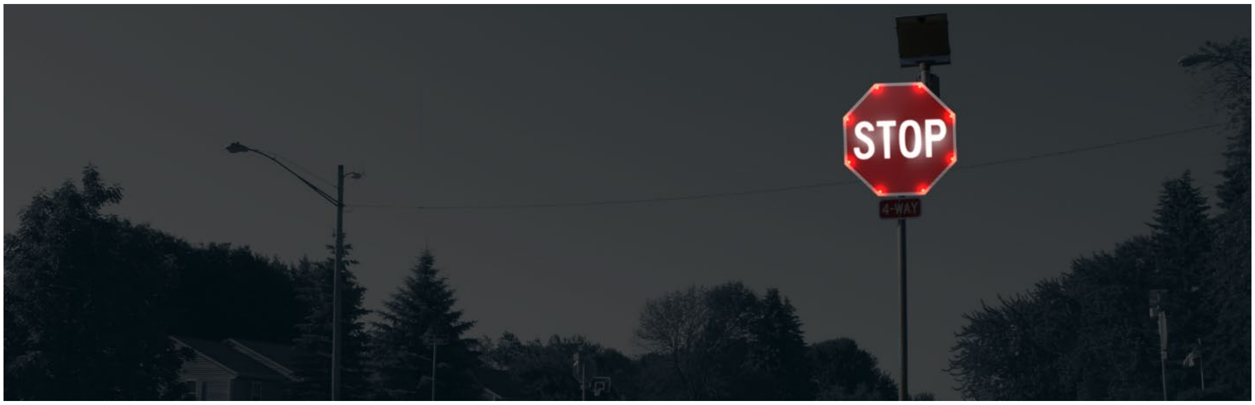
Question 15: As detailed in figure 15 one of the common practices for unused signs is to drape those signs with a black material, can such practice be a challenge for AVs?

Figure 15. Source: Joe Bruno

Question 16: Is it essential to have traffic signs to be on either side of highways or would the current MUTCD standards used for human drivers shall be applicable?

Question 17: What is your opinion on having illuminated traffic signs as shown in figure 17?

Figure 17. Source: Stinson ITS



Question 18: As shown in fig. 18, is it essential to have colored bike lanes to improve the AV performance near bike lanes?

Figure 18. Source: NACTO

Question 19: Performance of AVs at all way stop sign is too conservative probably possibility of missing social communication that is associated with human drivers, what could be a possible solution to improve the AV performance here?

Question 20: Is the current practice of delineating the work zones with vertical devices a challenge for AVs? what is your opinion on having orange colored pavement markings for work zones?

Question 21: What are your thoughts on having digitized traffic signs? Would it be beneficial under adverse weather conditions?

Question 22: Contrast of roadside barriers has been a concern for AVs? Do you recommend any solution for them?

Question 23: Do we need to have consistency in the horizontal and vertical positioning of traffic signal heads?

Question 24: Another aspect to recognize which traffic signal head points to which lane, according to you is this a point of concern for AVs. If so, what could be a solution or improvement?

Question 25: Do we need to segregate bike traffic as shown in figure 25 with vertical devices or curbs in the AV future, or the current standards supplemented with traffic signages should be sufficient?

Figure 25. Source: Boston.gov

APPENDIX 2: Driving Behavior Parameters

Table 65 Recommended driving behavior parameters for following in Vissim

Parameter (Wiedemann 99 following model)		Rail-safe	Cautious	Normal	All-knowing	Default
CC0	standstill distance (ft)	4.9	4.9	4.9	3.3	4.9
CC1	spacing time (s)	1.5	1.5	0.9	0.7	0.9
CC2	following variation (ft)	0.0	0.0	0.0	0.0	13.1
CC3	threshold for entering “following” (s)	-10.0	-10.0	-8.0	-6.0	-8.0
CC4	negative “following” threshold (ft/s)	-0.3	-0.3	-0.3	-0.3	-1.1
CC5	positive “following” threshold (ft/s)	0.3	0.3	0.3	0.3	1.1
CC6	speed dependency of oscillation (10^-4 rad/s)	0.0	0.0	0.0	0.0	11.4
CC7	oscillation acceleration (ft/s2)	0.3	0.3	0.3	0.3	0.8
CC8	standstill acceleration (ft/s2)	6.6	9.8	11.5	13.1	11.5
CC9	acceleration at 80 km/h or 49.70 mph (ft/s2)	3.9	3.9	4.9	6.6	4.9

Table 66 Recommended driving behavior parameters for lane change in Vissim

Behavioral functionality	Rail-safe	Cautious	Normal	All-knowing	Default
Advance merging	n.a.	On/off	On	On	On
Cooperative lane change	n.a.	On/off	On	On	Off
Safety distance reduction factor	n.a.	1 + EABD	0.6	0.75	0.6
Min. headway (front/rear)	n.a.	1	0.5	0.5	0.5
Max. deceleration for cooperative braking	n.a.	−2.5	−3	−6	−3
EABD: Enforce Absolute Breaking Distance					

Table 67 Vissim Driving Behaviors

Driving Behaviors		Number of interaction objects	Number of interaction vehicles	Vehicle Following Model
Autonomous driving	AV cautious	2	1	Weidemann 99
	AV normal	2	1	Weidemann 99
	AV aggressive	10	8	Weidemann 99
Human Driving	Urban (motorized)	4	99	Weidemann 74
	Right-side rule (motorized)	2	99	Weidemann 99
	Freeway (free lane selection)	2	99	Weidemann 99

APPENDIX X. VALUE OF RESEARCH (VoR) ESTIMATE

X.1 INTRODUCTION

In accordance with the scope of TxDOT Project 0-7080, Develop Roadway and Parking Design Criteria to Accommodate Automated and Autonomous Vehicles, the research team at UTSA has prepared an estimate for the VoR associated with the research products delivered for this project.

The benefit areas deemed relevant and identified in the project agreement for the purpose of establishing the VoR encompass both qualitative and economic areas. The benefit areas identified for this project are summarized in Table X.1.

Table X.1. Selected Benefit Areas for Project 0-7080.

Selected	Benefit Area	Qualitative	Economic	Both	TxDOT	State	Both
X	Level of Knowledge	X			X		
X	Management and Policy	X			X		
X	Quality of Life	X			X		
X	Customer Satisfaction	X			X		
X	Environmental Sustainability	X				X	
X	System Reliability		X		X		
X	Traffic and Congestion Reduction		X			X	
X	Freight movement and Economic Vitality		X				X
X	Intelligent Transportation Systems		X				X
X	Safety		X				X

X.2 QUALITATIVE BENEFIT AREAS

X.2.1 Level of Knowledge

One of the primary outcomes to Project 0-7080 was to provide recommendations for updates to design specifications in order to better accommodate Autonomous Vehicles (AVs). The project team evaluated the current status of the AV sensing technology and matched it with the current specifications summarized by the TxDOT Design Guide and other national publications such as the "Green Book" and the TMUTCD.

X.2.2 Management and Policy

Project 0-7080 developed specific traffic microsimulation for selected urban corridors calibrating specific parameters such as vehicle gaps to address different levels of AV penetration. The microsimulation models demonstrated the effects on traffic Levels of Service (LOSs). Results may be used to direct management and policy decisions by an agency as TxDOT to guide investment on road infrastructure specifically targeted to increase AV performance.

X.2.3 Quality of Life

The implementation of the recommendations of Project 0-7080 would have a significant impact on quality of life, by increasing capacity of existing road and parking infrastructure and providing mobility access to underserved segments of the population, addressing issues related to the future shift in the age distribution of the residents of Texas.

X.2.4 Customer Satisfaction

The implementation of the recommendations of Project 0-7080 would have a significant impact on customer satisfaction considering the aspects addressed in the Quality of Life benefit paragraph.

X.2.5 Environmental Sustainability

The implementation of the recommendations of Project 0-7080 would have a significant impact on Environmental Sustainability considering the possible reduction in road capacity demand associated with AVs and associated reductions in the carbon footprint and the reduction of emissions.

X.3 ECONOMIC BENEFITS

Economic analysis pertaining to four functional areas relevant to the performance of this project and identified in the project agreement was requested.

- System Reliability.
- Traffic and Congestion Reduction.
- Freight Movement and Economic Vitality.
- Intelligent Transportation Systems.
- Safety

For analyzing these functional areas, the research team generated Figure X.1. The considerations that went into the computation of the VoR (explained in greater detail below) can be summarized as follows.

If a road is congested or traffic is interrupted by crash events, it cannot serve its purpose of moving people and goods. This reduces commercial transport of goods and services and causes travel delays that affect productivity and may be quantified monetarily.

The possibility of increasing capacity and reductions in travel time have a significant economical impact. The results of project 0-7080 contribute to improve capacity, reduce crashes and reduce travel time with significant economical benefits to the State of Texas.

Project #	0-7080		
Project Name:	Develop Roadway and Parking Design Criteria to Accommodate Automated and Autonomous Vehicles		
Agency:		Project Budget	$ 328,696
Project Duration (Yrs)	2.0	Exp. Value (per Yr)	$ 23,000,000
Expected Value Duration (Yrs)	20	Discount Rate	5%
Economic Value			
Total Savings:	$ 206,671,304	Net Present Value (NPV):	$ 169,872,805
Payback Period (Yrs):	0.014291	Cost Benefit Ratio (CBR, $1 : $___):	$ 517

Years	Expected Value
0	$22,671,304
1	$0
2	$23,000,000
3	$23,000,000
4	$23,000,000
5	$23,000,000
6	$23,000,000
7	$23,000,000
8	$23,000,000
9	$23,000,000
10	$23,000,000
11	$23,000,000
12	$23,000,000
13	$23,000,000
14	$23,000,000
15	$23,000,000
16	$23,000,000
17	$23,000,000
18	$23,000,000
19	$23,000,000
20	$23,000,000
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23	$0
24	$0
25	$0
26	$0
27	$0
28	$0
29	$0
30	$0

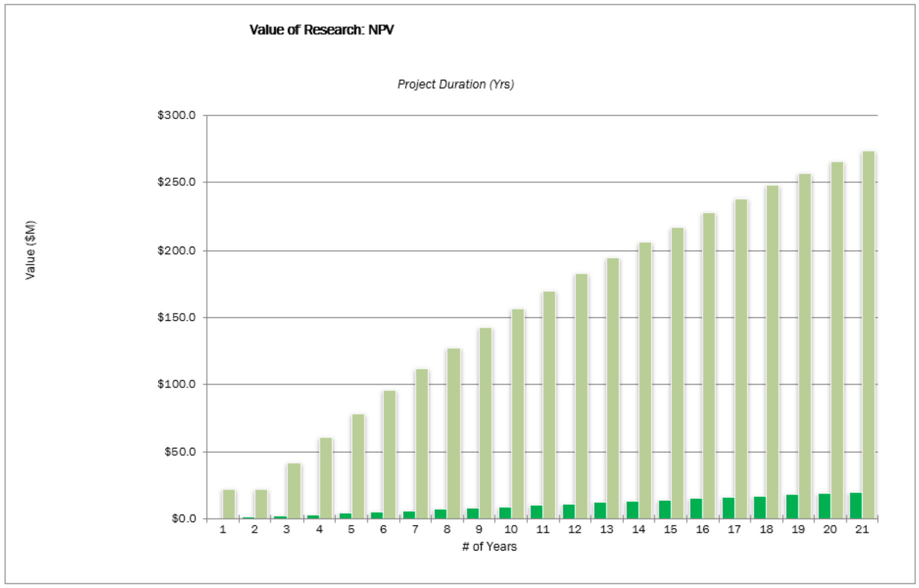

Figure X.1. Summary of VoR Calculations for Project 0-7080.

X.4 COMPUTED VOR

The values assigned in Figure G.1 are attributed to two primary sources:

• The economic improvement resulting from the efficient implementation of road infrastructure to accommodate AVs and the associated benefits of reducing travel times and increased road capacity. Project 0-7080 results are a strong contribution to the successful implementation of AVs.

• The costs attributed to reduction in crashes with a reduction of human and associated congestion costs.

According to the recently published HB 2223 Study: Motor Vehicle Impacts on the Roads and Bridges of Texas, (https://ftp.txdot.gov/pub/txdot/gov/hb-2223-final-report.pdf), the annual congestion costs for passenger and commercial traffic is estimated to be $21 billion dollars. Assuming a reduction in congestion by the implementation of the recommendations of project 0-7080 of just 0.11 percent would achieve annual savings of $23 million, this without taking into account the reduction of crashes and associated human and congestion costs.