The Future of Parking: Safety Benefits and Challenges

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16. Abstract

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Introduction

Parking facilities are part of transportation infrastructure in which both drivers and pedestrians must be cautious at all times. Slower speeds in parking lots also give people a false sense of security. A National Safety Council (*1*) survey revealed that 66% of drivers would use their phones while driving through parking lots. This situation is clearly reflected in non-motor traffic crash statistics (i.e., crashes that occur off-public roadways), as most non-traffic motor crashes occur in parking facilities or on private roads. According to the National Highway Safety Administration (*2*), in 2015 there were over 2,000 fatalities and nearly 95,000 injuries in non-traffic-related crashes. Additionally, a recent crash study (*3*) found that 64% of backing-related crashes occurred in parking lots. While crashes between two vehicles account for some of these, pedestrians are sometimes involved.

The parking experience is expected to be improved by new technologies such as autonomous vehicle (AV) features like self-driving and self-parking. According to an International Parking & Mobility Institute survey (*4*) conducted nationwide, parking experts expect that the top emerging changes that will influence parking will be the increased use of ride-hailing and AVs. Over 50% of participants believed that AVs and self-parking technologies would have a significant effect on parking in 10 years. The different levels of vehicle automation that affect parking behavior can be grouped under two main categories: (i) driver assistance and (ii) self-parking. The former requires a driver who is assisted by the vehicle in parking by using sensors and/or cameras. Many of today's vehicles have these parking assistance features. Self-parking, on the other hand, is only provided by vehicles with self-driving options that allow drivers to leave the car at any location where they vehicle will then park by itself. Self-parking vehicles do not need to be close to their drivers while parking; instead, they can drive themselves to less congested and cheaper parking facilities that are farther away.

The ability of vehicles to self-drive and self-park at a distance from the operator's destination can lead to innovative approaches for the organization and management of parking facilities. Therefore, the design and the management of parking facilities will need to change. Although current guidelines are not applicable to self-parking vehicles, it is expected that AVs with a self-parking feature will fall within the existing layout and design criteria. However, to maximize parking efficiency, new parking design for AV-use-only parking facilities should be examined. Researchers have been working on finding the most effective layout for self-parking. One study (*5*) showed that, by only changing the layout of the traditional parking facilities, self-parking car parks could decrease the required parking space by an average of 62% and a maximum of 87%. Additionally, while there will be less need for on-street parking in downtown areas, the need for drop-off zones is expected to be increase with the increased use of self-driving vehicles. Space currently allocated for parking could become space for pick-up and drop-off lanes, which will need to be strategically located near the entrances to downtown destinations.

Self-driving and self-parking vehicles will become increasingly prevalent in the transportation system. It is expected that self-driving/-parking vehicles and non-AVs will share the country's roads for a number of years until they reach 100% market penetration. However, fully realizing the benefits expected from the arrival of AVs will also require the development of roadway and parking infrastructure that can adequately accommodate AVs as they gradually integrate into the transportation system. The goal of this research is to explore parking facility design for self-parking vehicles and operational change recommendations to improve parking safety. Herein, the research team identifies potential design changes and self-parking penetration scenarios. Expected parking and street design changes are assessed in terms of the reduced number of conflicts for pedestrians and other vehicles using microsimulation techniques.

Background

Importance of Parking

Since every vehicle trip is associated with parking at the trip origin and destination, parking facilities are considered as important infrastructure components of the highway transportation system. According to a survey conducted by the American Automobile Association (AAA) (*6*) the average time a vehicle spent traveling on roadways was approximately 59 minutes/day during 2019–2020. For the rest of the day, this vehicle is parked in a space. As a vehicle spends an average of 96% of a day occupying a parking space, an extensive amount of land is necessary to meet parking needs. According to Inci et al. (*7*), in the United States, parking lots take up more land area than the State of Massachusetts. A more recent study (*8*) has found that, in some cities in the United States, parking density (parking spaces per acre) is twice as much as the population density (persons per acre).

One of the major issues related to parking is the lack of information about the infrastructure inventory (i.e., location of spaces). In the United States, no city has collected or maintained a comprehensive database of its parking supply, including privately owned spaces within its city limits (*9*). Consequently, the national estimate is made based on simple extrapolations from the population statistics. One of the best estimates made by Chester (*10*) states that the number of parking spaces in the United States ranges from 722 million to 2 billion.

Parking Safety

For the past decade, studies and policies have worked to bring awareness to vehicle related non-traffic accidents (accidents that occur off of public roadways), which typically occur in parking lots and private driveways. While anyone can be at risk for this type of accident, children in particular are in the most danger, and have been the spark plug to implementing new policies that aim to reduce these accidents. According to KidsandCars (*11*), from 1997 to 2021, there were 1,502 back over (vehicles pulling out of parking spot) fatalities involving children aged 14 and under in the United States. Most of these accidents occur while a vehicle is parking or exiting a parking lot. Findley et al. (*12*) aimed to identify the safest and most dangerous parking maneuvers.

Researchers collected crash data for parking lots in the vicinity of a university campus and compared that with observational parking position data. After analysis, pull-in/back out were identified as the parking maneuvers most likely to result in a collision, as opposed to back-in/pull-out maneuvers, which were deemed the safer option. After further evaluation, it was discovered that 90% of North Carolina's parking related fatal and serious injuries occurred during a back-out maneuver. According to an AAA survey (*13*), over 76% of U.S. drivers tend to park their vehicles by pulling forward instead of backing into a parking spot.

One of the issues with drivers using the pull-in/back out parking maneuver is the lack of driver visibility. In recent years, new advances in technology have mitigated this to a certain extent. Rear cross-traffic alert systems are designed to help drivers back out of spaces where it may be difficult to see approaching traffic, as sometimes happens in parking lots. These alert systems use sensors to monitor two areas behind the driver for vehicles approaching from the right or left. Cicchino (*3*) aimed to find the impact rear cross-traffic alert systems have on backing crashes by comparing police-reported backing crash rates in 25 U.S. states between certain vehicles with and without rear cross-traffic alert systems. The presence of other parking assistance systems was accounted for and controlled. On average, rates for backing crashes were 22% lower among vehicles with rear cross-traffic alert than without and 32% lower with the system than without when the vehicles were traveling in perpendicular directions.

While rear-view cameras will be implemented into all new vehicles (*14*), it has become apparent that warning systems and cameras alone may be limited by drivers' slow reaction time, as well as by different blind spots in the systems. AAA tested rear cross-traffic alert systems and found that the technology failed to detect pedestrians an alarming 60% of the time (*6*). This is partially due to some systems not being designed to detect pedestrians. Additionally, the systems failed to detect a passing vehicle 30% of the time. Another study (*15*), found that while rear-view camera displays play a factor in reducing rates of collisions with unexpected obstacles during backup as long as drivers are attentive, this increases the risk of colliding with an object that cannot be seen in the camera's blind spots or vehicles approaching from other directions (e.g., a vehicle outside the camera's field of vision).

At the moment, only rear-view cameras are required in vehicles, but studies have shown that when multiple technologies are combined, the number of accidents are vastly reduced. Cicchino (*16*) compared the effects of rearview cameras, rear parking sensors, and rear automatic braking systems in backing crashes by comparing police-reported backing crash involvements among vehicles using the different backing assistance systems in 23 U.S .states from 2012 to 2015. When vehicles used rear parking sensors alone, the police-reported backing crashes were reduced by 28%. On the other hand, when vehicles used rear view cameras alone, backing crashes were only reduced by 5%. When these two systems were combined, however, police-reported backing crashes were reduced by 42%. Finally, when they were combined with rear automatic braking, backing crash involvement rates were 78% lower than for vehicles with none of the systems. These results indicate that the less technology has to rely on an appropriate response from the driver, the more effective it is. This can be due to many human errors, from reaction time to inattention. According to Hendricks et al. (*17*), driver inattention is the leading component in vehicle crashes. This carelessness is amplified in parking lots, as drivers tend to feel a false sense of security. In a nationwide survey done by the National Safety Council (*18*), participants said they would perform the following actions while driving in a parking lot:

- Make a phone call (66%)
- Text (56%)
- Check email (50%)
- Video chat (42%)
- Take photos/videos (49%)

Innovative, state-of-the-art rear parking assistance technologies can only do so much if the driver fails to respond in time. Newer technologies aim to require less input from the driver, eventually requiring none, but fully self-driving and parking AVs are still years away. Fagnant and Kockelman (*19*) suggest that AVs could reduce fatal crash rates by 40% due to their independence from driver error. But for the moment, drivers should be more aware of the dangers of driving in parking lots to improve safety.

Autonomous Vehicles and Self-Parking

AVs that allow some level of self-driving and self-parking will soon join the transportation system in the U.S. It is expected that AVs and traditional vehicles will share the country's roadways for a number of years, until AVs reach 100% market penetration. However, fully realizing the benefits expected from the arrival of AVs will also require the development of roadway and parking infrastructure that can adequately accommodate these vehicles as they gradually integrate into the transportation system.

AVs are expected to have major social impacts in the form of crash savings, travel time reduction, fuel efficiency, and parking benefits. Fagnant and Kockelman (*19*) believe annual economic benefits from AVs could be in the range of $27 billion with only 10% market penetration, with the potential to save the U.S. economy around $450 billion annually when including broader benefits and a higher penetration rate. As the market penetration of AVs increases, transportation facilities, parking facilities in particular, will experience significant benefits. AVs are expected to drop off their passengers at a designated area and head to a parking facility by themselves. This behavior change will lead vehicle owners to send their vehicles to cheaper parking facilities, which are expected to be outside of city centers. This is expected to save private AV users about $18 daily in parking costs, but may also increase vehicle travel by 2.5% due to the roundtrip travel between the owner's destination and the parking facility (*20*).

The era of personally owned fully autonomous vehicles is still decades away. Many manufacturers, however, are aggressively developing links to, and extensions of, the automated driving systems available in today's vehicles, such as lane keeping, cooperative adaptive cruise control, automatic emergency braking, and more. Manufacturers are also continually expanding the baseline capabilities to be able to provide an SAE Level 4 experience. At SAE Level 4, a vehicle can monitor the environment and operate autonomously, under certain conditions, without the human driver needing to take back control (*21*). Eventually, the continued incremental evolution of these capabilities and an expansion of the operational design domain (ODD) in which they can operate will lead to a Level 5, fully autonomous vehicle, where the vehicle can drive by itself, in all environments, at all times, without human intervention.

One uncertainty that emerges with the self-parking behavior is what will happen after the vehicle drops off its users. AVs will have some options as to what will happen until they are needed again. By using a traffic microsimulation model and data from downtown San Francisco, Millard-Ball (*20*) aimed to find the most optimal decision the AV can make after dropping off a user in a typical downtown of a big city. The cheapest option for 13% of trips was free on-street parking, though this kind of parking is limited. Returning home was not a viable option for most AVs (8%), as this requires the users to live close to the area and have short stays at their destinations; otherwise, it is an expensive approach. For most trips (40%), cruising was the least expensive option. The study concluded that congestion and high parking prices could be relieved by a future where most AVs consist of automated taxis, rather than of individually owned vehicles.

Since AVs will not go immediately to 100% market penetration, it may take some time to design and construct special parking facilities for self-parking. In the meantime, it is expected that a combination of both human-driven vehicles and some level of AVs is a condition that may persist for quite some time. This complicates the design environment, as decisions made for a fully autonomous vehicle fleet may not be the same as decisions made for a mixed fleet, which may also not be reflective of the decisions made for a fully human-driven fleet.

Parking Design

In an autonomous future, it is believed that a centralized taxi service without drivers, or shared AVs will be commonly used. This new travel mode will be more affordable and environmentally friendly due to the reduced number of vehicles on the road. For every shared AV on the road, it is believed that there will be 11 less privately owned vehicles (*22*). Moreover, there will likely be fewer parking lots for passenger vehicles since auto ownership will decrease. However, where passenger vehicle parking is needed, the criteria will still involve vehicle size, turning radius, and time of occupancy. AVs will park themselves, so parking design might realize benefits. With the self-parking capabilities of AVs, the capacity of parking facilities will increase because the average space required per vehicle will be less, driving lanes will be narrower, and there won't be a need for stairs and elevators.

A recent survey conducted by the World Economic Forum revealed that 43.5% of the respondents felt that the biggest benefit of AV technology will be self-parking capabilities (*23*). As noted previously, vehicles will no longer need to be in close proximity to their drivers and can instead, drive themselves to less congested and cheaper parking lots that are farther away (*19*). The ability of AVs to park themselves at a distance from their passenger's final destination can lead to innovative approaches for the organization and management of parking facilities. Therefore, the design and management of parking facilities will need to change. Although current guidelines are not readily applicable to self-parking, it is expected that AVs can fit into the existing layout and design criteria.

The layout of the parking facility will change its overall space efficiency. The current layout requires a lot of islands and roadways within the parking facility to make sure each vehicle can maneuver and exit without any conflict. Researchers have focused on finding the most optimal layout for new AV car parks. One important strategy that would lead to large space savings is to stack the AVs in several rows, one behind the other. Nourinejad et al. (*5*) proposed a car-park layout by using a mathematical model with the assumptions that all vehicle sizes are the same, the car-park operator takes control of all AVs, the AVs arrive at the car-park following a Poisson distribution, and the car-park is designed exclusively for AVs. They proposed a multi-row layout with vehicles stacked behind each other. In order to avoid blockage, this requires the operator to relocate some of the vehicles to create a clear pathway for a blocked vehicle to exit, as shown in Figure 1. To move the blocked green car, two cars (red) are relocated and wait in the alley to allow the green car to leave. The simulation findings revealed that these new car parks can decrease required parking space by an average of 62% and a maximum of 87%.

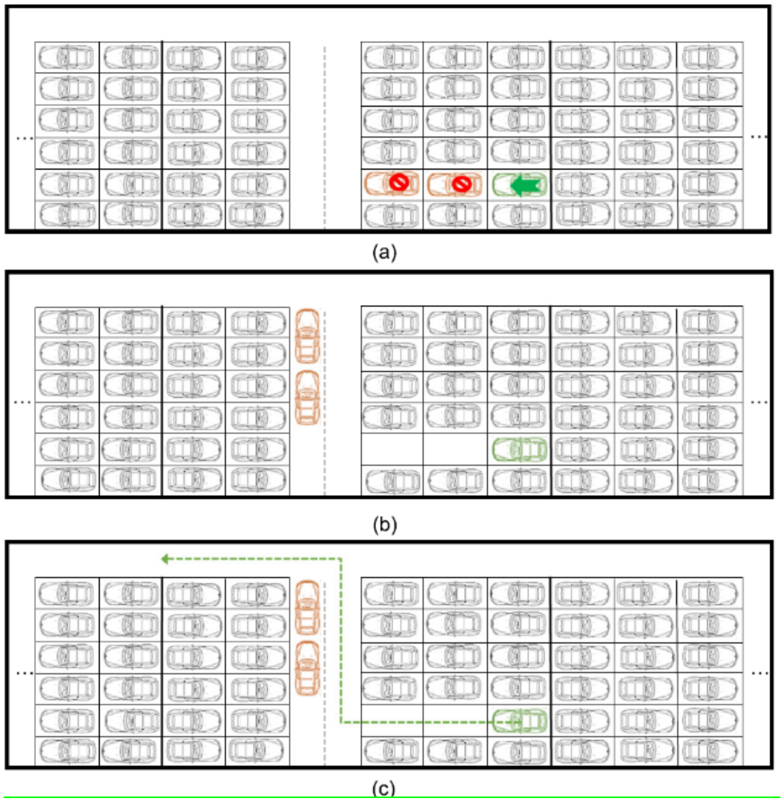


Figure 1. Self-parking vehicle egress movement in a stacked parking facility (*24*).

In another design plan, Audi calculated the reduction of car space per vehicle as 2 square meters and assumed that there will not be any need for elevators, or staircases in the parking facilities.

The Urban Futures Initiative established by Audi estimates that the need for parking space will decrease to 70% by 2030 in the district the initiative takes place (*26*). However, to save some space for parking, new guidelines for self-parking-use-only parking facilities should be established.

With less need for on-street parking, cities will need effective curbside management policies to use lanes currently used for parking. It is expected that business districts and main attraction zones will need designated pick up and drop off areas for AV users. The need for drop-off lanes is expected to be greater with AVs, so space currently allocated for curbside parking could become space for AV pick-up and drop-off. These drop-off lanes need to be strategically located near the entrances of popular destinations (*27*).

For AVs, cities and states have started to develop effective curbside management practices in anticipation of a change in use of on-street parking spaces. Curbside management is the concept of creating a hierarchy for improving the safe and efficient movement of people and goods by optimizing curb space. Managing on-street infrastructure requires the integration of many different stakeholders, perspectives, and demands. These include those factors related to urban freight deliveries, land use, economic development, and the Americans with Disabilities Act. The curb is not just a physical piece of infrastructure, but also a flexible space that can change iteratively or temporarily. The methods and techniques for managing on-street parking spaces can include striping treatments for cordoning locations for parking, pedestrian and bicycle movements, as well as taxi/ride-hail vehicles and loading zones for freight delivery.

Design requirements for parking and staging areas need to be updated. Within the urban environment, accommodating truck delivery of goods to merchants will also need to be modified post-automation. Future delivery by automated trucks will require better designated delivery parking areas, improved curb management procedures, and will likely need to be designed in concert with local land use and development planners.

Modeling and Microsimulation

The use of microscopic traffic simulation models in transportation design, planning, and traffic operations has become widespread across the world. Increasing computer technology allows for the development of more sophisticated traffic tools. Simulation models allow mimicking the stochastic and dynamic nature of the vehicle-to-vehicle and vehicle-to-infrastructure interactions. Therefore, the AV technologies may easily be tested in simulation before being implementing in the real world. The research team will explain the benefits and use of microsimulation modeling for AV environments by exploring previously conducted studies.

Modeling techniques have been widely used for the evaluation of alternatives in transport planning, management, and logistics. Using these tools, researchers create and analyze different traffic scenarios, and provide results to decision makers and stakeholders (*28*). Researchers can also evaluate the performance of transportation networks. During the last decade, microscopic traffic simulation models have been extensively used to evaluate the impact of Intelligent Transportation Systems (ITS) on traffic operations (*29*) and AVs (*30*).

Regarding parking facilities, researchers have used modeling techniques to estimate parking demand. For instance, Best and Moreno (*31*) used the VISSIM traffic simulation software package to evaluate truck parking demand along the tolled section of the New York State Thruway. In this study, researchers also provided guidance in model development. Moreover, researchers have used modeling techniques to evaluate novel parking management systems for maximizing parking capacity (*32*). For example, Chai et al. (*33*) used the SUMO traffic simulation software package to successfully test a proposed dynamic parking and route guidance system.

Modeling AVs has generated much interest and intense research activity in the area recently. There are a number of studies that develop frameworks and algorithms to realistically replicate AV behavior in mixed traffic scenarios where vehicles with different levels of automation share the road (i.e., mixed traffic). Shelton et al. (*34*) evaluated changes in average speed along a 12-mile section of I-35 in Austin for six scenarios with different AV market penetrations. In order to realistically replicate AV driving behavior in the model, researchers developed an algorithm that accounts for cooperative adaptive cruise control, speed harmonization, and queue warning application AV capabilities. More recently, in 2020, researchers proposed a novel approach to model AVs in mixed traffic (*35*). In the specific area of AVs and parking, researchers used modeling techniques to quantify the reduction of parking spot search time for AVs (*36*) (*37*).

Modeling techniques have been widely used to test AVs at freeways, highways, and parking facilities among other locations. Testing and evaluating AVs in a simulation environment offers some advantages. First, researchers have complete control of all aspects of the test and the test can be repeated as many times as required. Second, the use of modeling techniques allows researchers to create different scenarios that may be required to test AVs in different facilities such as on-street parking or parking garages while in mixed traffic with different self-parking market penetration. Finally, researchers can test AVs using modeling techniques with a minimum amount of resources when compared with tests performed in a real-world environment. For all these reasons, researchers used modeling techniques in conducting this project.

Method

Model Overview

This study evaluated the benefits of potential AV use and parking design/layout changes using The University of Texas at El Paso (UTEP) campus as a case study. The UTEP campus, having an urban setting with 25,000 student enrollment, provides all types of parking facilities, including on-street parking, off-street parking, and parking garages. Given the potential changes to parking layouts made necessary by greater market penetration of AVs, this research evaluated the improvements made to safety through the reduced number of exposures for pedestrians and conflicts with other vehicles. The safety performance of the recommended design improvements and operational policy changes are presented as outcomes of the study. However, these recommendations should not be viewed as official guidelines. Researchers selected one parking facility or zone for each type to develop simulation models. In total, including the base scenarios (existing conditions), the research team coded 15 simulation models; the safety performance of each model is reported.

Parking scenarios were developed using the microscopic software platform VISSIM. The research team opted to use a previously designed microsimulation model of the campus, which was developed by a former UTEP student (*38*). After reviewing campus traffic and parking data, researchers improved the model and developed the parking network design for the study.

Parking Scenarios

The research team aimed to explore how self-driving vehicles can impact parking facility design and operational change recommendations to improve parking safety. Newer versions of VISSIM provide users with built-in AV parameters. Researchers carefully reviewed the differences between regular vehicles and self-driving AVs in VISSIM and used the software's default parameters for the simulation. By implementing AVs into the model, the number of conflict points between vehicles could be analyzed. In order to fully determine the potential safety benefits of AVs, 15 modeling scenarios with different AV market penetration and parking operational changes were identified and simulated. Table 1 describes each simulation scenario. Each parking facility has five different scenarios, with different vehicle compositions, and layout/design improvements.

Table 1. Parking Scenarios

Scenario	Parking type	Self-parking market penetration	Layout change
Base 1	On-street	0%	No
AV 1	On-street	25%	No
AV 2	On-street	25%	Yes
AV 3	On-street	75%	No
AV 4	On-street	75%	Yes
Base 2	Off-street	0%	No
AV 5	Off-street	25%	No
AV 6	Off-street	25%	Yes
AV 7	Off-street	75%	No
AV 8	Off-street	75%	Yes
Base 3	Parking garage	0%	No
AV 9	Parking garage	25%	No
AV 10	Parking garage	25%	Yes
AV 11	Parking garage	75%	No
AV 12	Parking garage	75%	Yes

Network Construction

The UTEP campus model has five distinct vehicle entry points, as well as 24 different parking lots used as destinations. For the purpose of this project, the research team selected and constructed three separate parking options: on-street parking, off-street parking, and a parking garage. Aerial images were used as reference points to develop each parking facility. Figure 2 displays an aerial image of the UTEP campus, which contains all three parking facilities selected for this study. The following sections describe each parking facility as well as the different scenario changes that were made.

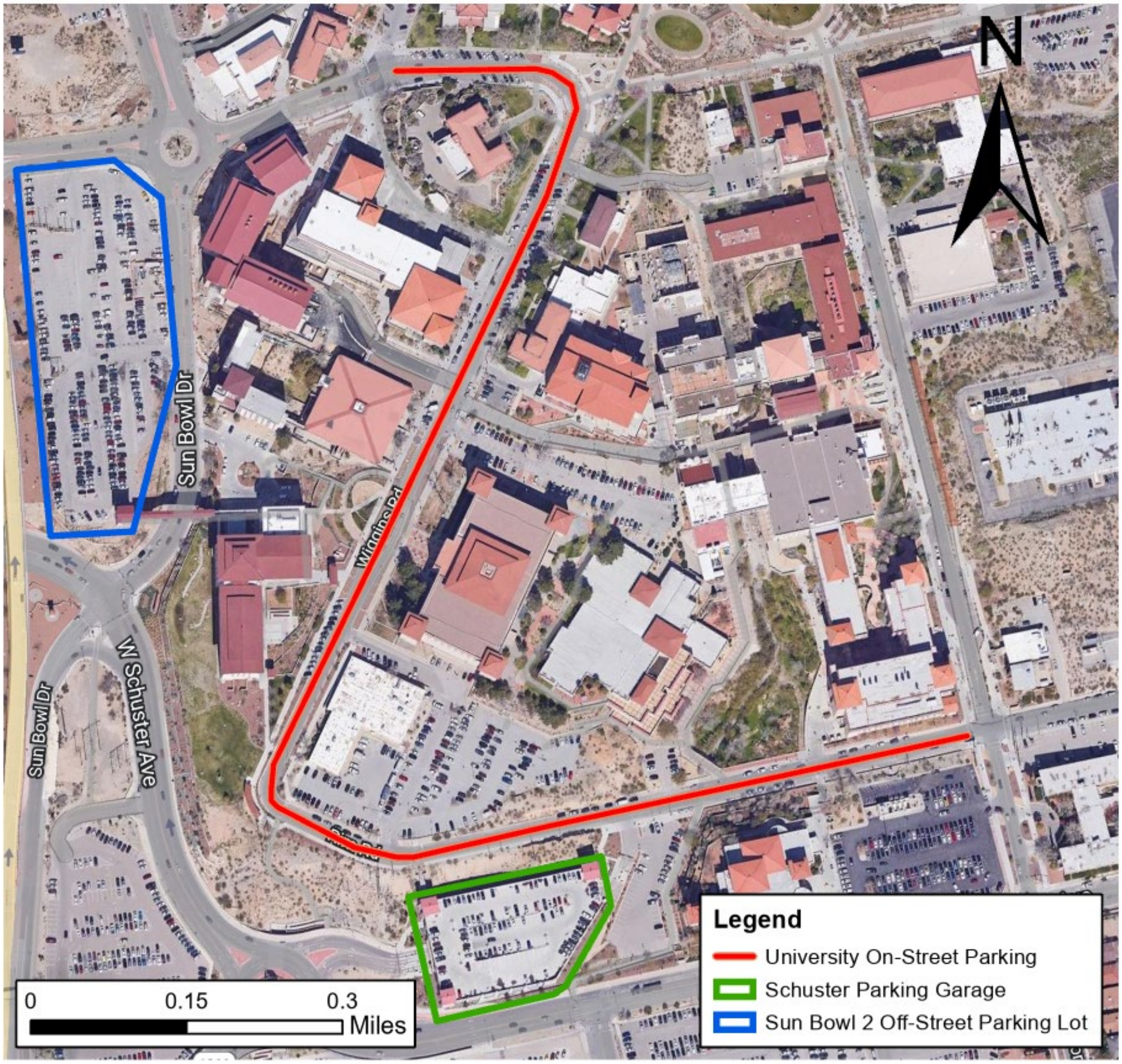


Figure 2. UTEP campus aerial image.

On-street Parking

The UTEP campus has on-street parking that cuts through the middle of the University. Figure 2 displays the parking area selected for on-street parking simulation, indicated by the red line that cuts through the UTEP campus. The parking takes place through University Ave., Wiggins Rd., and finishes at Rim Rd. This area has a mix of angled and parallel parking for drivers to choose from. Since this is inside the campus, drivers must take additional care to avoid any pedestrians making their way through the campus. There are two ways to enter this school parking facility: through Rim Rd. or University Ave. This parking type had a total of five modeling scenarios.

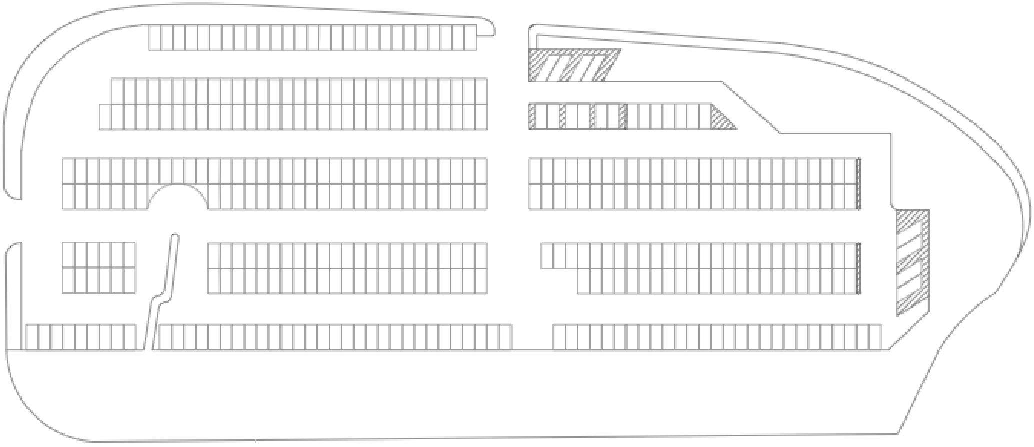
Initially, the model was computed without any design improvements and with three different AV market penetrations: 0%, 25%, and 75%. Researchers then attempted to improve parking safety by implementing operational changes to the model. For this parking type, AVs were designed to park outside the school campus, while non-AVs remained inside the campus. This could be a common scenario in the future as AVs drop off their users and park at a designated parking facility. This design change was executed for market penetrations of 25% and 75%. This study did not consider a special layout or design change for the on-street parking, and therefore no capacity increase was expected with different AV scenarios.

Off-street Parking

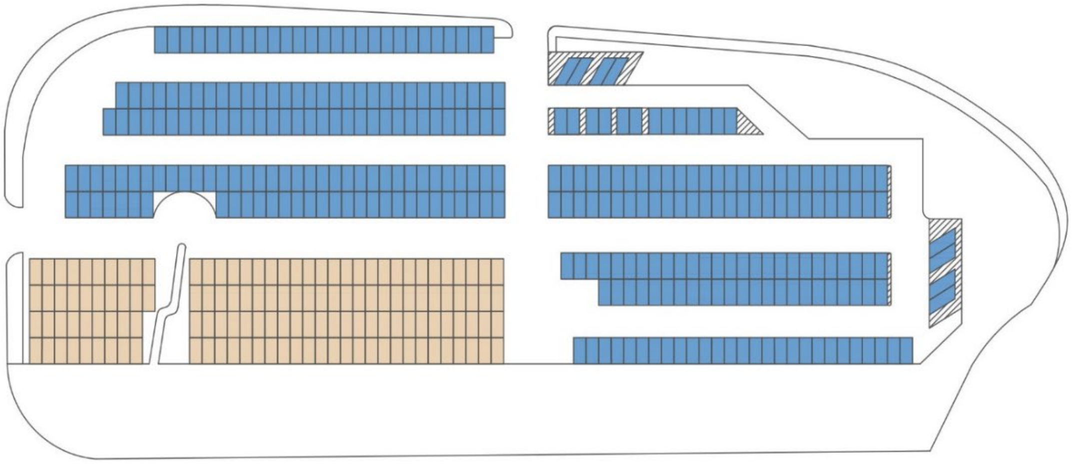
The UTEP campus has several off-street parking facilities to choose from. For this study, the off-street parking facility selected was Sun Bowl 2, located off Sun Bowl Dr. near I-10. Figure 2 illustrates the location of the parking facility as portrayed by the blue polygon in the aerial image. It has a mix of angled and 90-degree parking spaces for students and guests to utilize. This parking lot has a total of 402 parking spaces. It has two entry points: the entrance off Sun Bowl Dr. and another after the I-10 exit. This is a popular parking lot due to its size and convenient location.

Including the base scenario (existing scenario), five modeling scenarios were developed for this parking facility, the first three without any layout changes and the two market penetrations for AVs (25% and 75%). For the operational changes due to the layout change, the AVs were instructed to park in the northwest corner of the parking lot, closest to the freeway entrance. Figure 3 demonstrates the alternative layouts for the selected parking facility, which were used for the scenario developments and network construction. Figure 3(a) is the demonstration of the existing parking layout, whereas Figure 3(b) and Figure 3(c) were developed for the potential introduction of AVs with 25% and 75% market penetration respectively. The blue colors represent the spaces dedicated for the non-AVs and the spaces highlighted with orange are for the AVs.

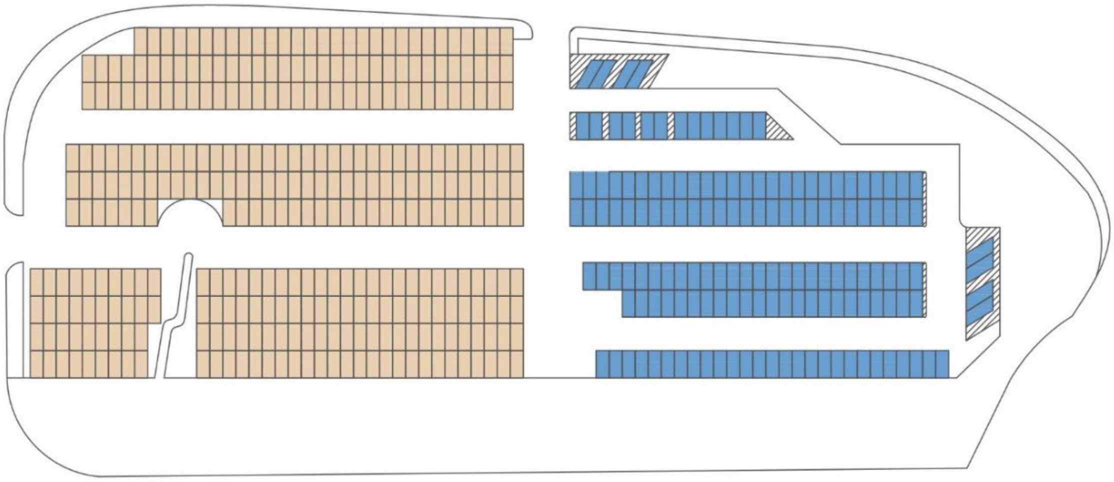
The recommended changes in the layout take into consideration the multiple rows of vehicles stacked behind each other. Considering the existing structures and optimal car-park layout to have minimum cost for the layout change and minimum relocations for the parked AVs, the designated AV spaces are all grouped together. With these changes, for the selected off-street parking, the overall capacity is increased by 10% and 20% based on the 25% and 75% AV market penetration scenarios.



(a) Off-street parking Base scenario (No AVs)



(b) Off-street parking 25% AVs with layout change (Scenario AV6)



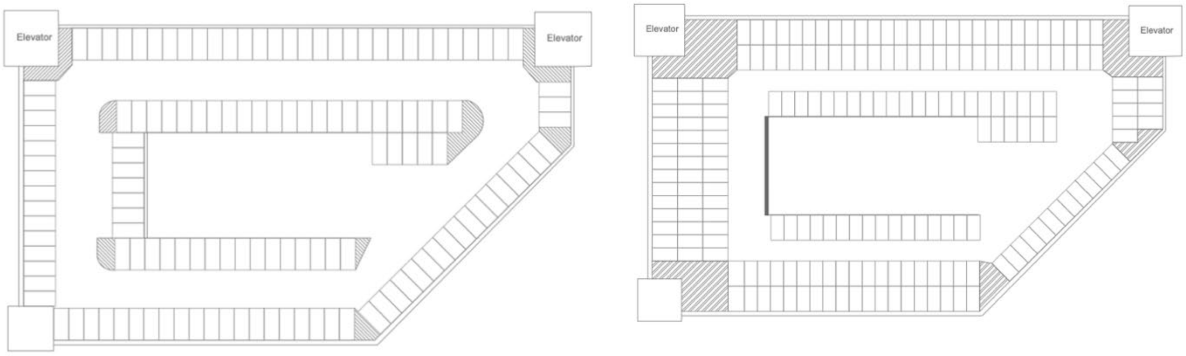
(c) Off-street parking 75% AVs with layout change (Scenario AV8)

Figure 3. Off-street parking layout alternatives.

Parking Garage

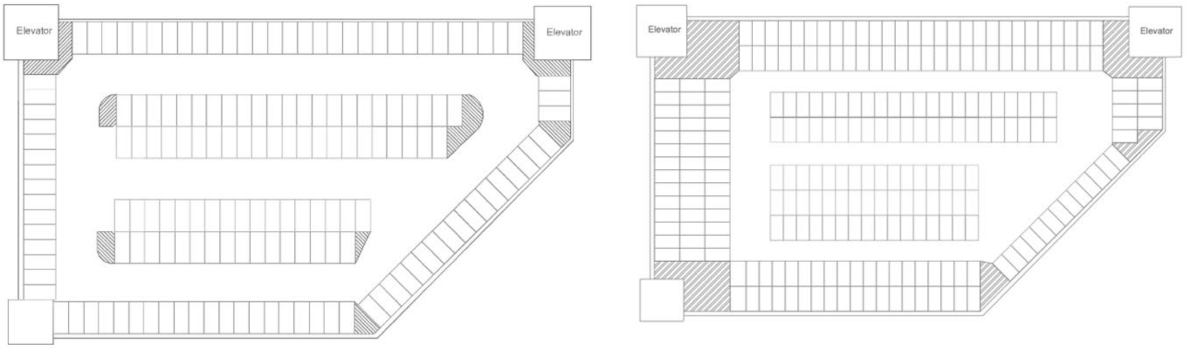
UTEP has two popular parking garages on campus that are routinely sold out annually: Schuster and Sun Bowl Parking Garages. Due to its simplicity compared to the Sun Bowl Garage, Schuster Garage was chosen as the parking garage case for this study. Figure 2 displays an aerial image that shows the Schuster Garage as outlined by a green polygon. The garage is made up of five parking levels and a total of 700 parking spaces. The garage is located off Schuster Dr. and has one entrance. Similarly to the other parking facilities utilized for this study, five different scenarios were modeled. The initial three scenarios modeled the three different market penetrations with no operational/layout changes. In the fourth scenario, the model had a 25% AV market penetration (Scenario AV10), and the top floor was to be used only by AVs. For the final scenario (Scenario AV12), campus experienced a 75% AV rate and the top two floors were designed to be used only by AVs. With these recommended changes, the overall parking garage capacity increased from 9% (AV10) to 19% (AV12).

Figure 4 demonstrates the layout transformations with the 25% and 75% AV scenarios. Figure 4(b) and Figure 4(d) are the recommended layout improvements for the AV use-only floors for the top and the middle floor respectively.



(a) Actual layout (top floor)

(b) Alternative layout (top floor)



(c) Actual layout (middle floor)

(d) Alternative layout (middle floor)

Figure 4. Parking garage layout alternatives.

Conflict Study

In order to evaluate the impact of AVs on roadway safety, VISSIM microsimulation software was used to model different scenarios with varying market-penetration rates. VISSIM was used to model three different parking scenarios: on-street parking, an open surface parking lot, and a parking garage. Each scenario was modeled to have varying market penetration rates of 0% (no AVs), 25%, and 75% for a total of 15 unique scenarios. This study followed the methodology developed by Morando et al. (*39*). To determine the total number of conflict points for each scenario, the Surrogate Safety Assessment Model (SSAM) was used (*40*). This application was developed by the Federal Highway Administration to identify and analyze traffic conflicts using vehicle trajectory data output from microscopic traffic simulation models, in this case VISSIM. For this project, the SSAM software code was accessed for free online through GitHub (https://github.com/OSADP/SSAM). Upon downloading the necessary code, SSAM was operated via an executable file and its corresponding libraries. Each trajectory file from the 15 unique scenarios was then used as input into the SSAM software and processed individually.

SSAM processes the vehicle trajectory files using predefined time to collision (TTC) and post encroachment time (PET) threshold values. The default values of 1.5 seconds for TTC and 5 seconds for PET were used in this analysis. SSAM also allows users to define rear end angle and crossing angle conflict thresholds, for which the default values of 30 and 80, respectively, were used. Once these values were defined, SSAM processed each individual trajectory file and identified a conflict point by identifying whether the paths of two vehicles overlapped during the predefined TTC duration. If a conflict was detected, SSAM recorded data about the conflict, such as type (crossing, rear-end, or lane change), conflict angle, conflict location, as well as speed and acceleration of both vehicles before and after the conflict occurred.

Pedestrian Exposure Analysis

In order to determine the impact of AVs on pedestrian safety, it was necessary to measure the exposure of the pedestrians who would be at risk. Pedestrian risk can be defined as the ratio of crashes at a particular location to the relative exposure. A study conducted by Molino et. Al (*41*) defines exposure as hundred million pedestrian or bicycle miles of roadway traveled, or more precisely as hundred million miles of shared facilities traveled, such as driveways, alleys and parking facilities. To determine the exposure for parking lots and parking garages in particular, the average walking distance was determined for pedestrians traversing predetermined zones. Then, the annual pedestrian distance in millions of miles was determined based on parking facility population in Washington, D.C. However, this method does not include vehicle usage of the facilities and assumes the pedestrians were exposed at a constant rate.

This study proposes a new methodology for determining the relative pedestrian exposure for a particular parking facility in terms of vehicles instead of pedestrian miles traveled. This methodology utilizes a similar approach by using pedestrian walking time within a particular facility, but also incorporates the rate at which vehicles are expected to enter the shared facility.

This way, the pedestrian exposure can be directly related to the number of vehicles that are expected to come in contact with pedestrians. The methodology can be modeled by the equation below, where x_i is the walking time of a driver from their parked car to the exit of the parking facility. The sum of the walking time for each parked vehicle and the time that the facility is occupied is $(\frac{P}{t})$, with the p as the number of parked vehicles, used to find the vehicle pedestrian exposure.

$$Exposure = \sum_{i}^{P} x_i * \frac{P}{t} \qquad (1)$$

Results

Conflict Study

After each trajectory file was analyzed by the software, SSAM organized the data in a downloadable CSV (comma-separated values) file. Users may filter the data by setting threshold values for TTC, PET, and other surrogate values. The unfiltered dataset was downloaded for each scenario, along with a summary file provided by SSAM that included minimum, maximum, mean and variance values for each surrogate safety measure for the entire dataset. Within the summary file, the total number of conflicts was recorded and separated by each type of conflict. The table below shows the total number of conflicts determined by SSAM for each scenario in this study. Results suggest that AVs improved the safety significantly for the entire system with high penetration rates. Considering the base scenarios, AVs reduced the number of conflict points by 7% to 45% with AV penetration rates of 25% and 75% respectively. The changes were consistent through different parking types (see Table 2).

Table 2. Total Number of Conflicts for Each Scenario

Scenario	Parking Type	AV %	Layout change	Capacity Increase	Conflicts	Reduction
Base 1	On-street	0%	No	-	3,920	-
Base 2	Off-street	0%	No	-	4,071	-
Base 3	Parking Garage	0%	No	-	3,977	-
AV 1	On-street	25%	No	-	3,615	8%
AV 2	On-street	25%	Yes	-	3,620	8%
AV 3	On-street	75%	No	-	2,154	45%
AV 4	On-street	75%	Yes	-	2,154	45%
AV 5	Off-street	25%	No	-	3,795	7%
AV 6	Off-street	25%	Yes	10%	3,803	7%
AV 7	Off-street	75%	No	-	2,260	44%
AV 8	Off-street	75%	Yes	20%	2,317	43%
AV 9	Parking Garage	25%	No	-	3,682	7%
AV 10	Parking Garage	25%	Yes	9%	3,679	7%
AV 11	Parking Garage	75%	No	-	2,198	45%

AV 12	Parking Garage	75%	Yes	19%	2,220	44%

Pedestrian Exposure Analysis

Considering the driver behavior of the on-street parking users, pedestrian exposure analysis was tested only for off-street parking facilities and parking garages. Same parking facilities were selected on the UTEP campus with varying levels of AV market penetration rates; (i) off-street parking lot with 402 parking spaces, and (ii) parking garage consisting of 700 parking spaces. Pedestrian walking times from each parking space were collected by measuring the distance to the nearest pedestrian exit of the parking facility on Google Earth Pro. Each walking distance was then converted to walking time by assuming an average pedestrian speed of 4 ft/s. The walking times were then summed for the entire facility to obtain total x_i for each scenario.

Without any design improvements, a mixed traffic environment, and AVs able to park at any parking space, there would be no significant reduction in pedestrian exposure except for the introduction of AVs to the system. Therefore, pedestrian exposure analysis was conducted only for the scenarios with design improvements for off-street parking and parking garages. For the AV 6 scenario with 25% AV involvement, only the parking spaces under non-AV use were summed since it is assumed that nearly one quarter of the parking lot would be occupied by AVs. Therefore, there would be no drivers and consequently no pedestrian walking time for those spaces (see Figure 3). The same process was used to calculate the exposure for the AV 8 scenario. Only the spaces closest to the pedestrian exit assigned to non-AV use were summed, assuming the rest would be dedicated to AVs (see Figure 4).

For the off-street parking lot, the total walking time for the base scenario was calculated to be 632.76 minutes. For the 25% and 75% AV scenarios, the total walking times were 431.01 and 174.90 minutes, respectively. For the parking garage, the walking times were determined for each of the floors of the facility. The 25% scenario dedicates the entire top floor to AVs and assumes the rest of the parking levels for regular drivers. Similarly, the 75% scenario dedicates the top two floors to AVs and leaves the remaining floors for regular drivers. The total walking times of the garage were determined to be 78.43 and 95.79 minutes for the top floor and third floor respectively.

In addition to the total walking times for each parking facility, the arrival rate of vehicles per minute also had to be calculated. A previous study determined the arrival rates at both locations on the UTEP campus by manually counting the number of vehicles entering each parking lot and recording their time of entry (*42*). With this data, the arrival rates in terms of average vehicle/minute were determined and used as $\frac{P}{t}$ in equation (1). The average arrival rate for the morning peak of the open surface lot was found to be 2.7 veh/min. For the top two floors of the parking garage, the peak arrival rates were found to be 2.1 veh/min for the top floor and 4.2 veh/min for the third floor.

Once the total walking time, x_i, and vehicle arrival rate, $\frac{P}{t}$, were determined, the pedestrian exposure in terms of vehicle per person was calculated. For the off-street parking lot, the pedestrian exposure was 1,913 pedestrian vehicles for the base scenario. When introduced to 25% AVs, the exposure was reduced by 32% to 1,303 pedestrian vehicles. This figure was further reduced 72% to 529 pedestrian vehicles when the parking lot was converted to 75% AVs as in defined in Scenario AV 8. The exposure values were then calculated for the parking garage using the same approach. The top two floors had an average exposure of 165 and 393 pedestrian vehicles, respectively, while the bottom two floors had an average exposure of 402 and 249 pedestrian vehicles, respectively. For the base scenario, the total exposure was 1,209 pedestrian vehicles. For the 25% and 75% AV scenarios, the total exposure including only the floors of interest was 1,044 and 651 pedestrian vehicles, respectively. The table below summarizes the findings for each scenario.

Table 3. Exposure Values for Each Scenario

Scenario	Parking Type	AV %	Layout Change	Exposure	Reduction
Base 2	Off-street	0%	No	1,913	-
Base 3	Parking Garage	0%	No	1,209	-
AV 6	Off-street	25%	Yes	1,303	32%
AV 8	Off-street	75%	Yes	529	72%
AV 10	Parking Garage	25%	Yes	1,044	14%
AV 12	Parking Garage	75%	Yes	651	46%

Conclusions

The goal of this research was to explore the impact of self-parking vehicle systems on parking facility design and operational change recommendations to improve parking safety. The research team identified the potential design and layout changes and self-parking penetration scenarios. Expected changes of the parking design were assessed in terms of the reduced number of conflict points and pedestrian exposures using microsimulation techniques.

In order to evaluate the impact of AVs on roadway safety, VISSIM and SSAM were used to model different scenarios with varying market penetration rates. Each scenario was modeled to have varying market penetration rates of 0% (no AVs), 25%, and 75%, for a total of 15 unique scenarios. To determine the impact of AVs on pedestrian safety, this study proposed a new methodology for determining the relative pedestrian exposure for a particular parking facility. This was in order to directly relate the pedestrian exposure to the number of vehicles expected to come in contact with pedestrians.

Results suggest that, at higher penetration rates, AVs not only increase parking capacities but also improve safety significantly for the entire system. The capacity increase was calculated between 9% and 20% for the off-street and parking garages. Moreover, comparing the base scenarios, AVs can reduce the number of conflict points by 7% to 45% with AV penetration rates of 25% and 75% respectively. The changes were consistent through different parking types. The reduction in pedestrian-vehicle exposure ranged from 14% to 72% with the recommended layout improvements considering different AV penetration rates.

Additional Products

The Education and Workforce Development (EWD) and Technology Transfer (T2) products created as part of this project are described below and are listed on the Safe-D website here. The final project dataset is located on the Safe-D Dataverse.

Education and Workforce Development Products

This project provided support for full-time graduate student, Mario Vazquez, in the Department of Civil Engineering at UTEP toward his Master’s in Environmental and Civil Engineering. The student directly contributed to model construction, the literature review, and report writing. Throughout this project’s lifecycle, Mario became more familiar with the dangers of and statistics regarding accidents in and around parking facilities. Additionally, Mario became proficient in the basics of VISSIM modeling as well as the software’s parking modeling for static vehicle routing.

This project included direct involvement from two full-time undergraduate students in the Department of Civil Engineering at UTEP: Mario Vazquez and Danielle Madrid. Mario began the project as an undergraduate student and by the end was in his third semester as a graduate student. Danielle fulfilled her tasks of generating the simulation’s outputs to the team, contributed to the writing of the report, and provided the methodology. Danielle became familiar with SSAM, the output generated by VISSIM. She learned how to use the software to manage and export the data the project required. Danielle has now been admitted to UTEP’s Master’s program. She will be starting her graduate degree in Environmental and Civil Engineering in the summer of 2022.

The PI was given the opportunity to give a lecture for Dr. Kelvin Cheu’s Traffic Engineering graduate course. The presentation covered fundamental concepts of parking, including demand, supply, pricing, intelligent transportation systems in parking, and level of service. Additionally, the PI utilized parking accident data analyzed in this study to expose the students to the dangers of parking facilities, as well as the importance of improving parking safety, particularly to those most vulnerable. Furthermore, students were familiarized with the future of self-driving vehicles and how they can potentially impact the safety of parking facilities and revolutionize how parking infrastructure layouts are designed.

Through multiple conferences, Mario was able to work on and improve his technical communication skills. He and the PI presented the project to the ITE UTEP Student Chapter on April 21, 2022. Those present included Dr. Cheu, Dr. Weidner, and Dr. Ke from the Civil Engineering Department. Researchers were provided with the professors’ input on the project as well as on potential future studies.

Technology Transfer Products

Graduate student, Mario Vazquez presented at UTEP's Research Grad Expo, where UTEP graduate students are given the opportunity to display their research studies to other researchers and professionals. Students can improve their technical speaking skills and network in a professional environment. Mario was exposed to professional conferences on a smaller scale and used this opportunity to enhance his professional skills to the best of his ability. Figure 5 displays Mario at the UTEP Grad Expo next to the research team's poster board.

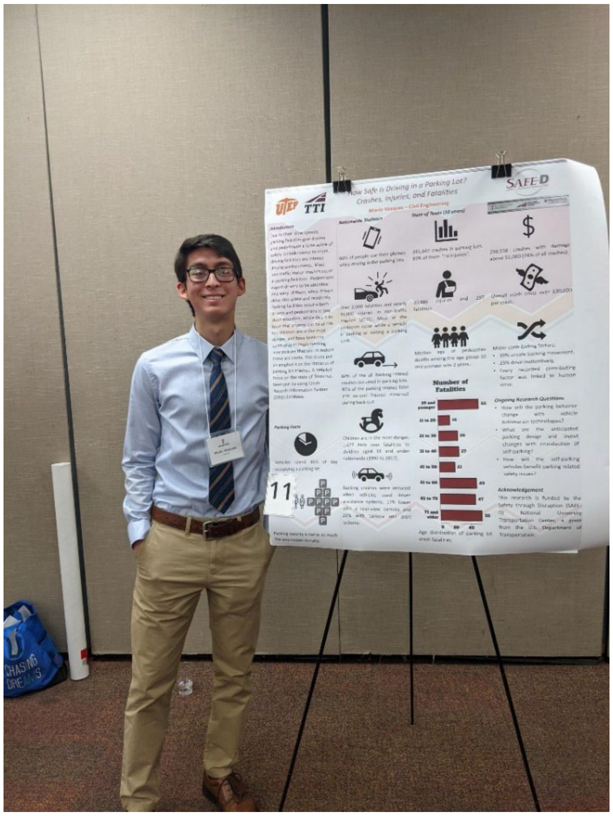
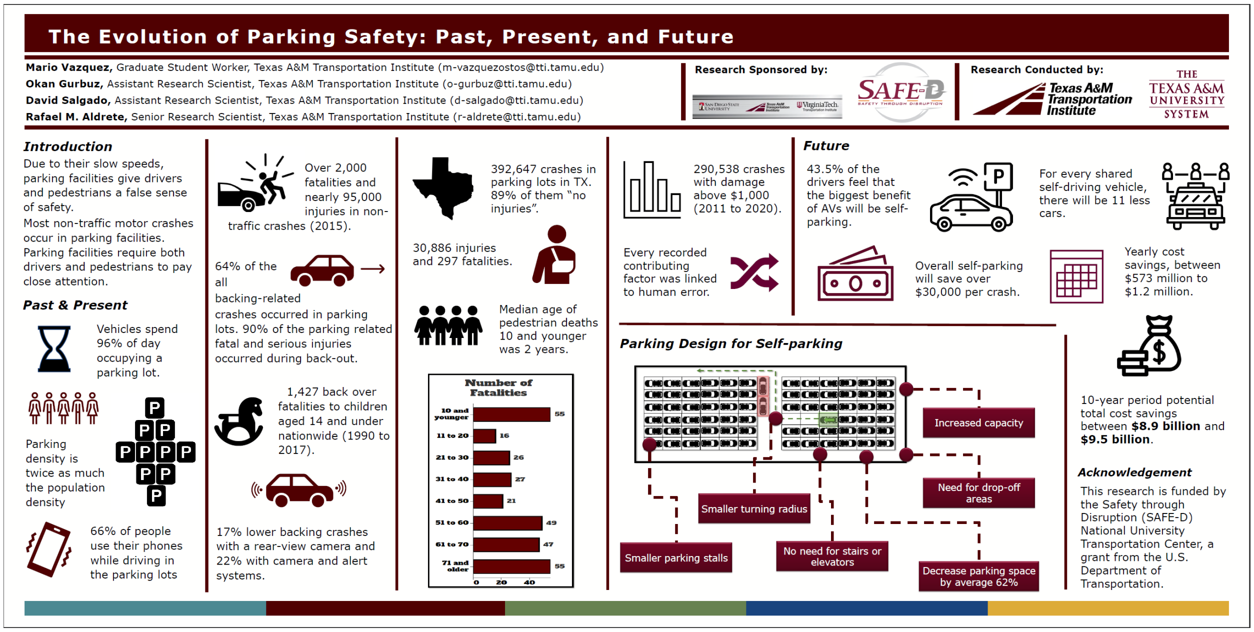


Figure 5. Graduate student, Mario Vazquez, at UTEP Research Grad Expo.

The research team submitted a paper to the Transportation Research Board (TRB) in Washington D.C. After approval, researchers assembled a poster board which depicted the main aspects of this study. Since the model construction and output were still in the development process, the model simulation was omitted from the poster. This conference was held from January 8–12, 2022. The research team was scheduled to present this study on January 11 between 1:30 PM-3:00 PM. Figure 6 presents the poster board the team put together.



The Evolution of Parking Safety: Past, Present, and Future

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Research Sponsored by:

Research Conducted by:

Introduction

Due to their slow speeds, parking facilities give drivers and pedestrians a false sense of safety.

Most non-traffic motor crashes occur in parking facilities. Parking facilities require both drivers and pedestrians to pay close attention.

Past & Present

Vehicles spend 96% of day occupying a parking lot.

Parking density is twice as much the population density

66% of people use their phones while driving in the parking lots

Over 2,000 fatalities and nearly 95,000 injuries in non-traffic crashes (2015).

64% of the all backing-related crashes occurred in parking lots. 90% of the parking related fatal and serious injuries occurred during back-out.

1,427 back over fatalities to children aged 14 and under nationwide (1990 to 2017).

17% lower backing crashes with a rear-view camera and 22% with camera and alert systems.

392,647 crashes in parking lots in TX. 89% of them "no injuries".

30,886 injuries and 297 fatalities.

Median age of pedestrian deaths 10 and younger was 2 years.

290,538 crashes with damage above $1,000 (2011 to 2020).

Every recorded contributing factor was linked to human error.

Future

43.5% of the drivers feel that the biggest benefit of AVs will be self-parking.

For every shared self-driving vehicle, there will be 11 less cars.

Overall self-parking will save over $30,000 per crash.

Yearly cost savings, between $573 million to $1.2 million.

Parking Design for Self-parking

Increased capacity

Smaller turning radius

Need for drop-off areas

Smaller parking stalls

No need for stairs or elevators

Decrease parking space by average 62%

10-year period potential total cost savings between **$8.9 billion** and **$9.5 billion**.

Acknowledgement

This research is funded by the Safety through Disruption (SAFE-D) National University Transportation Center, a grant from the U.S. Department of Transportation.

Figure 6. TRB poster board.

Data Products

VISSIM was used to model three different parking scenarios: on-street parking, an open surface parking lot, and a parking garage. Each scenario was modeled to have varying market penetration rates of 0% (no AVs), 25%, and 75% for a total of 15 unique scenarios. To determine the total number of conflict points for each scenario, the Surrogate Safety Assessment Model (SSAM) was used. This application was developed by the Federal Highway Administration to identify and analyze traffic conflicts using vehicle trajectory data output from microscopic traffic simulation models, in this case VISSIM. SSAM was operated via an executable file and its corresponding libraries. Each trajectory file from the 15 unique scenarios was then used as input into the SSAM software and processed individually. SSAM processes the vehicle trajectory files using predefined time to collision (TTC) and post encroachment time (PET) threshold values. The default values of 1.5 seconds for TTC and 5 seconds for PET were used in this analysis. Once these values were defined, SSAM processed each individual trajectory file and identified a conflict point by identifying whether the paths of two vehicles overlapped during the predefined TTC duration. If a conflict was detected, SSAM recorded data about the conflict, such as type (crossing, rear-end, or lane change), conflict angle, conflict location, as well as speed and acceleration of both vehicles before and after the conflict occurred. Pedestrian exposure analysis was tested only for off-street parking facilities and parking garages. Same parking facilities were selected on the UTEP campus with varying levels of AV market penetration rates; (i) off-street parking lot with 402 parking spaces, and (ii) parking garage consisting of 700 parking spaces. Pedestrian walking times from each parking space were collected by measuring the distance to the nearest pedestrian exit of the parking facility. Each walking distance was then converted to walking time. The walking times were then summed for the entire facility to obtain total walking times. All the findings and more information can be found on the dataverse here.

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