Hit the Deck: Impacts of Autonomous Vehicle Technology on Parking and Commercial Real Estate

by

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B.S., Urban Planning, 2011

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Submitted to the Program in Real Estate Development in Conjunction with the Center for Real Estate in Partial Fulfillment of the Requirements for the Degree of Master of Science in Real Estate Development

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Signature of Author

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HIT THE DECK:

Impacts of Autonomous Vehicle Technology on Parking and Commercial Real Estate

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ABSTRACT

The United States has a large supply of parking and with the adoption of autonomous vehicles, the demand for these spaces could change dramatically. Parking is among the most prevalent land uses occupying up to 31% of urban area. It is estimated that there are 3.4 to 8 parking spaces for each car in the US yielding 800 million to 2 billion spaces that could cover an area the size of West Virginia (Chester, Horvath, & Madanat, 2010). With fully autonomous vehicles expected on the consumer market by 2020, the $30 billion parking industry will experience enormous changes as cars evolve.

This thesis models the effects of autonomous vehicles on the financial performance of urban parking garages. The future of parking and autonomous vehicles will be anything but smooth or certain, and this work harnesses the power of uncertainty through repeated random number simulation in financially modeling autonomous vehicles’ impacts on parking garages.

The results indicate that parking in the short term is a risky investment and in the longer term may not be a viable asset. As the only class of real estate explicitly built for vehicles, they have a high degree of exposure to changes created by autonomous vehicles. This is illustrated by significantly negative net present values and minimal returns of the simulation outputs. This exposure will continue to grow as the stock of parking spaces increases with minimum parking requirements for new construction. Recommendations from this research would be to limit new supply of parking to allow for greater utilization of existing stock, more beneficial use of urban land, and better use of construction and financial resources.

Thesis Supervisor: Dr. Andrea Chegut
Title: Research Scientist, MIT Center for Real Estate
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I am lucky to have incredible classmates and comrades who made this year a joy. I am fortunate to have been under the tutelage of the Center for Real Estate staff and faculty. Your friendship, leadership, and mentorship have made a tremendous impression on me and I’m certain I will know you for the rest of my life.

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To all my friends who are my biggest heroes and greatest examples. To Bowser, for your kind words that made me believe that I belong. To Alex, for your infallible optimism and always believing in me. To Vera, Ariel, and Basil, for setting the bar high and never letting me settle. To Tim, for always listening, guiding, and loving me completely.

Finally, to my family whose endless encouragement and listening ears were only a phone call away. Thank you for helping me on this journey and loving me exactly as I am.

To the future, and the task ahead.

“We work in the dark - we do what we can - we give what we have. Our doubt is our passion and our passion is our task. The rest is the madness of art.”

- Henry James, The Middle Years, 1895.
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1. Introduction

Context
By 2020, a number of major auto manufacturers have officially announced to have the next generation of fully autonomous vehicles on the market1. The Society of Automotive Engineers (SAE) defines full automation as “Level 5”: where the car that can make all critical safety decisions and the “driver” can take their hands off the wheel, foot off the pedal, and eyes off the road. From luxury Mercedes to the working-class Hyundai, the $1 trillion automotive industry (Bureau of Economic Analysis, 2016) has made a strong commitment to autonomous, electric vehicles by the year 2020. This can be accomplished through strategic partnerships like GM’s $500 million deal with Lyft or Toyota and Microsoft’s $1 billion investment in research and development that include two new autonomous vehicle research centers (Viereckl, Ahlemann, Koster, & Jursch, 2015). Autonomous vehicles, although seemingly a nascent trend, are the result of almost a century of research combined with recent advancements in computer software, hardware, and data storage capacity.

Problem
With Level 5, fully autonomous vehicles on the cusp of consumer deployment, research has begun to grapple with the economic and spatial impacts of driverless technology. Financial research on the topic ranges from effects on related industries (Kockelman & Clements, 2017), to household savings (Arbib & Seba, 2017), to vehicle cost per mile (Boesch, Ciari, & Axhausen, 2016). Spatial predictions deal with urban rent dynamics (Zakharenko, 2016), ideal land use locations (Heinrichs & Cyganski, 2015), and planning and policy recommendations (Kockelman, 2013). These studies have explored the impact of autonomous vehicles at different scales, but only a few have analyzed these issues at the building level (Henderson & Spencer, 2016).

In particular, limited attention has been paid to the economic impact of autonomous vehicles upon commercial real estate. Importantly, commercial real estate represents the largest subsection of our economy and the $4.2 trillion dollar industry is set for enormous financial and physical change catalyzed by autonomous vehicles. This study targets the singular connection point between cars and commercial real estate - parking. In commercial real estate, we focus on the five main product categories: residential, retail, office, hotel, and industrial. Parking is financially integrated into each project, yet rarely evaluated beyond initial construction. In urban areas, parking is often structurally incorporated and inseparable from other building uses. Thus, changes to parking can be felt throughout the real estate industry. Citing a report by Mckinsey (Bertoncello and Wee, 2015), Henderson and Spencer (2016) estimate that autonomous vehicles have the potential to reduce parking space by 42% by 20352 in the US, putting these buildings financially at risk. So rather than limit this analysis to one specific class of real estate, I will focus on parking where a shift in demand in a single land use, will be felt everywhere. To understand the rate and magnitude of future changes in parking in an autonomous vehicle future, I created a financial model that simulates the current and future financial status of structured parking garages in the US.

My Contribution
In this thesis, I forecast the financial impact of autonomous vehicles on parking garages. This is unique in that parking garages are not often considered an individual asset class in commercial real estate. Furthermore, the research devoted to autonomous vehicle implications at the property level is extremely limited. Using informed random number simulations, otherwise known as Monte Carlo simulation, to help predict unknown future outcomes is well-established by Geltner and de Neufville (2018) and their work in modeling uncertainty in real estate. My work applies this principle not only to the outcomes of the simulation, but also an extension to the model by simulating the

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1 Manufacturers committed to have a commercially viable autonomous car on the roads by 2020: Audi, Ford, Nissan, Tesla and Volkswagen.
2 This is due to the increased utilisation of vehicle miles completed by ride sharing platforms (e.g Uber), provides less incentive to own a vehicle.
variation to the inputs. In this way, the model can remain objective regarding future changes and end results while maintaining established parameters.

**Method of Analysis**

This model produces three scenarios for parking garages. First, as they are today with no changes anticipated for the future. Second, as they are expected to be in an autonomous vehicle future without the ability to sell the asset. And lastly, modeling the asset with an autonomous vehicle future and the ability to sell the asset at any point in time.

Much of my research is devoted to establishing a financial baseline for the state of parking today. Using a 10-year discounted cash flow model, I modeled the financial performance of a typical parking garage that assumed no changes related to autonomous vehicles. This base case pro forma, assumed a 250-space structured parking facility in an urban environment using national averages of property performance such as revenue, vacancy, and expenses.

Next, I forecast what happens to the asset with the adoption of autonomous vehicles. To model the future of parking, I developed an identification strategy for the predictions of autonomous vehicles adoption and disruption. I then applied the parking-specific parameters synthesized from this strategy using repeated random sampling to two discounted cash flow models of parking garages. The first model simulated exposed the asset to changes triggered by autonomous vehicles over a fixed 25-year period. The second model simulated the same changes but allowed for flexibility to either hold or sell the asset between 2 and 25 years. Finally, the results of these simulations subjected to market level dynamics using another repeated random sampling representing 10,000 results each.

**Results**

The average outcome of this analysis represented a deeply negative net present value of a parking structure. The relative investment periods provide a backdrop for the results where the base case pro forma was 10 years, the inflexible scenario was 24 years, and the flexible scenario was an average of 6.7 years with 25% of cases selling in year two. The average NPV for the three scenarios representing 100,000 outcomes each, were -$954,646 for the base case forecast, -$5.3 million for the inflexible sale scenario, and -$3.9 million for the flexible sale scenario. There was a less than 5% probability that the property would achieve a positive NPV in the inflexible 24-year hold scenario, but with a shortened investment of seven years on average, the flexible scenario would generate a positive NPV 20% of the time with a 5% chance of yielding an excess of $5 million. Although the simulated property continued to produce revenue, even profit, the results of which were not high enough to combat the time value of capital. With aggregate cash flows of approximately $1 million per year in each scenario, the IRR of the property was 6.31% for the base case pro forma, 3.4% for the inflexible, and 1.5% for the flexible scenario.

**Discussion**

The period of this financial analysis extends to 2042, when the average of the literature surveyed herein predicts 55% of all vehicles on the road will be autonomous driving over 63% of miles traveled in the US at a cost of $0.27 per mile. By that time, parking demand will have decreased by 33%. Clearly, parking is set for some big changes, and there remains room for improvement, or even hope, of this largely under-considered asset class. The same technology that nearly brought their demise may offer opportunities.

As autonomous vehicles reduce the need for parking, they may also reduce the competition between parking providers as those who can sell or redevelop likely will in the short term. Leaving opportunity for those with optimal facilities to capture the remaining customers and even expand into new lines of business. Despite escalations in vacancy, modest rent growth, and increasing need for capital expenditures, parking garages will still provide a source of revenue for some. Well suited locations may continue to serve a need for autonomous vehicles.
vehicles but the optimal location will be greatly in flux. A paradox of decreased need for parking space, yet increased efficiency may help maintain cash flows.

The remainder of this thesis is outlined as follows. The first three chapters explore the current status of parking as a part of car culture including car ownership, parking as a land use, parking garages, and investment in them. In Chapter 3 we will set the stage for current car ownership, and its financial implications, and disruptive trends already at play. Chapter 4 explores the stock of parking space in US cities and the costs associated with it. Chapter 5 is an in depth look at the parking garage as a subset of parking and its special considerations for design. Chapter 6 addresses parking as an asset and its investment landscape.

The next two sections explore the future as it relates to the history, feasibility, and adoption of autonomous vehicles that set the stage for my financial forecast. Chapter 7 explains the history and current status of autonomous vehicles and the technology behind them. In Chapter 8, I explore in depth the triggers of autonomous vehicles that will catalyze the significant changes to be inflicted on parking.

The final section of this thesis establishes and explains my method, assumptions, and results for my financial forecast of parking and autonomous vehicles. Chapter 9 reviews the method for and concept for building the model; Chapter 10 explains my data, assumptions, and inputs; and Chapter 11 dissects the results. Lastly, Chapter 12 discusses these results and provides some concluding remarks on how to not just model the future, but prepare for it.
A Brief History of Cars, Cities, and Parking

2. Cars and the Economics of Ownership

In 1899, two bike mechanics from Massachusetts sold the first American made automobile (Foner & Garraty, 1991). In 1900, well over half of the US population lived in rural areas smaller than 2,500 inhabitants (Census, 2017). Commutes were limited by how far the legs of humans or horses could carry them; about 4 to 7 miles, and averaging about an hour a day (Marchetti, 1994). There were over 21 million horses in the US and only 8,000 registered vehicles, but by 1910, there were nearly half a million cars (US Federal Highway Administration, 2015).

Ownership
The proliferation of automobiles can be attributed to streamlining of and innovation in the production process that led to significant cost reductions. The Model T, released in 1908, was the first automobile to be made on a moving assembly line with standardized parts. It sold over 15 million units in its lifetime making it the most popular and affordable personal mode of transport in the early 20th century. The mass-production process reduced the cost of a Model T by 60% in less than a decade: from $850 in 1908 to $345 in 1916 (Lewis, 1976, p. 41-59). This meant more people could go further, faster, for less money. Connectivity increased as people were freed from the physical limitations of bipedal or quadrupedal transportation and commutes climbed. Installment plans were instituted by other automakers to compete with Ford in 1916 and by 1925 75% of all car sales were purchased on credit (Foner & Garraty, 1991). This made it possible for households to own more than one automobile which has become the standard for the US in the latter half of the 20th Century. Since 1978, there has been more than 1 vehicle per driver in the US. Recent estimates of registered vehicles are 1.2 per registered driver or 2.3 per household, putting the US among the top five countries in car ownership per capita ("Motor Vehicles per 1,000 People", 2014; Shoup, 2005).

Finance
The consumption of cars has changed the economic markets of the US both at the national and household levels. Motor Vehicles now make up about 3.5%, or just over $1 trillion, of US gross domestic product (Bureau of Economic Analysis, 2017). The inflation adjusted rate of the average passenger vehicle in the US has boomeranged over the past 100 years. Starting out in 1917 at $21,337 and hitting rock bottom in 1940 at $12,920 (Boundy, Davis and Diegal, 2015, p.10-4). The average price of automobiles has increased steadily since then. In 2012, the cost of a new car hit a record of over $30,000 in real terms, and continues to climb to $34,077 in 2016 (Edmunds, 2016).

As evidenced by the growing cost, consumer demand has also steadily increased and set new records. Every year since 2009, consecutive records have been set for new car sales in the US. Last year, 17.5 million vehicles were sold, valued at over $665 billion. Two-thirds of this was financed, the remaining leased (Experian, 2017). Given the ever-increasing cost of vehicles, US households are continuing to go further in debt for their transportation, and taking longer to pay it off. The average length of car loan has doubled in recent years from 35 months in 1971, 48 months in 1985, to 66 months in 2016. The average loan-to-value ratio of vehicles over the past few decades has been 90% for new, and 97% for used vehicles with the average interest rate being 4.87% and 8.88% respectively (FRED 1971-2011; Experian, 2017). According to figures published by the Federal Reserve Bank of New York, the number of car loans counts have exceeded the number of mortgage accounts in the US every year since 2012 (Guilford, 2017)
Access to transportation through increased debt affects the household budget. With peaking car prices, and increased leverage, it follows that the amount households spend for transportation is also increasing. The average US household spends about $8,956 per year on automobile related costs (Bureau of Labor Statistics, 2016). This estimate includes loans or lease payments, fuel, insurance, repairs, registration, taxes, and parking. As a percentage of income, lower income Americans spend more on transportation than upper income Americans as displayed in Figure 2 below. The upper third of Americans spend 8% of their income on transportation and this percentage has remained relatively constant (The Pew Charitable Trusts, 2016). For Americans in the lower third of the income strata, transportation expenses have increased in real terms every year since 2000 to over 15% of their income in 2014. (The Pew Charitable Trusts, 2016).

Extreme borrowing and financial burden of vehicles have led to the largest default in subprime car loans in decades. Over 5% defaults on subprime car loans meant lenders suffered a 9% loss in 2016 alone (Experian, 2017). With interest rates on the rise, this loss severity may
only grow as these loans mature and car ownership changes as travel behaviors shift. Two main shifts are happening in the transportation realm as the affordability of cars is out of reach for some and out of style for others.

**Shifts**

Tectonic shifts are happening in the transportation industry as car ownership becomes out of reach for some and out of style for others. Over the past several years, peak car ownership has been a topic of discussion, but as new car sales and yearly vehicle miles traveled hit record highs each year, it seems that “peaking” is a more accurate description. Some authors have written recently about arriving at peak car era (Johnson & Walker, 2017) and future opportunities for leveraging automated mobility to serve transportation needs. However, there are already changes underway within the transportation industry, and they deal primarily with who is driving.

**Fewer Drivers**

Although car ownership in aggregate is increasing, private ownership in some cities in the US is actually decreasing. From 2010 to 2015 households without a car have increased in metropolitan areas like New York, San Francisco, Los Angeles, and Washington DC and even in smaller cities like Detroit, Tampa, and Phoenix (Peterson, 2016). These car-free households may experience some trade off in exchanging higher housing costs of more convenient locations for personal car ownership. But their decision-making choices as a consumer is important to note. Another important decision regarding the future demand of cars is how many licensed drivers there are in the US. An aging population may signify a natural decrease in the number of drivers as baby boomers, the second largest generation, are unable to maintain legal driving abilities. A more telling trend is the divergence away from obtaining or maintaining a driver's license in younger persons. In a 2016 study from the University of Michigan, Sivak and Schoettle found there was a “continuous decrease in the percentage of persons with a driver’s license” from 1983 to 2014. Those decreases were most profound in youth where there was more than a 20% reduction in the number of 18-year-olds with a license (Sivak & Schoettle, 2016). Overall, the perception in the utility of driving is decreasing but the overall number of cars on the road and miles traveled are increasing. One trend that can help explain this phenomenon are the new emerging models of transportation.

**Transportation Network Companies**

The new transportation business model of mobility on demand has been pioneered by an unlikely source: technology companies. Unlike traditional taxi, black cab, or car services, these transportation network companies (TNCs) utilize privately owned fleets of vehicle, offering only a technology platform to link the drivers to riders. Also referred to as ride sharing, smartphone applications allow riders to achieve a greater degree of mobility and drivers a greater utility of their vehicle. It is interesting to note that Uber was founded in at the peak of the recession in 2009 and offered a unique economic solution to the financial distress of the time. Uber retains the largest market cap in the industry and is valued over $68 billion, with its closest competitor Lyft at just $7.5 billion (Huston, 2017). Others like Sidecar, Maven, and Gett have entered the market as its popularity increase. The industry as a whole is valued at $11.8 billion as of 2017 and is projected to grow to $25.9 billion by 2021 (Statista, 2017). The two largest TNCs in the US, Uber and Lyft, have over 427,0001 unique drivers serving 45 million users (Statista, 2017) making billions of trips since 2008. Since 2014, Schaller (2017) suggests that these app-based rider services have driven 1.19 billion million miles in New York City accounting for a 7% increase in traffic in New York City. During that same time, transit ridership decreased by 3% (APTA, 2017). This increase of traffic related to TNCs is also echoed in San Francisco Transit Authority’s study that found one in every 5 trips that begin or end in the city were by TNC (San Francisco Transportation Authority, 2017).

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1 See Carson & Bloomberg (2015), Uber has 327,000 active driver, Lyft has over 100,000 as of 2015.
Recent ride-sharing research provides some insight on the externalities of the increased usage and proliferation of mobility on demand. Increased TNC trips also increase traffic, pollution and commute time that has a negative impact on ridership. Thus, TNCs have increasingly pushed their shared ride services where multiple riders with different destinations are paired to the same driver. The continued growth of this industry depends on the ability to share rides and cut costs. Some companies have also made a strong commitment to reducing emissions and harnessing new technologies. Lyft also has made a strong commitment to electric and autonomous vehicles stating that by 2025, the company will have given 1 billion rides a year in electric, autonomous vehicles that reduce their greenhouse gas emissions by 5 million tons (Lyft Blog, 2017).
3. Parking: The Land Use of Cars

Human settlements have been structured around transportation since the beginning of cities. Apart from foot traffic or horses, the first major mode of transport was water by ships, then rail by steam engines, then roads by car, then air travel by plane (Glaeser & Shapiro, 2003). Despite the variety of transportation technologies, nothing has dominated the landscape of the American city like the automobile. Car culture in the US has shaped our economy, our cities, our buildings, and our daily routine. For being a large part of our daily lives, they are a small part of our economy, estimated at 3.5% or $1 trillion (Bureau of Economic Analysis, 2017). Real estate, building rentals, and leasing are estimated at 12.1% of our economy at a $3.5 trillion (Bureau of Economic Analysis, 2017). Cars clearly have an outsized impact on the built environment and have driven decisions of where and how US cities have grown for the last 100 years.

The original automobile was a catalyst for much of the economic growth and the distribution of people in the US over the 20th century (Hoyt, 1964). It changed the shape of cities as employers and households were increasingly mobilized in their search for lower rents and moved further from the center. Location didn't dominate urban development in the same way when one could travel further, faster and for less money. Location became less about the immediate physical surroundings measured in miles and more about the mobility measured in minutes. We began to adapt the design and size of our roads, homes, and businesses to support our dependence on the automobile. Roads became straighter and wider; homes became larger with two-car garages; and minimum parking standards increased the development of land in our cities. The conversion of undeveloped to developed land increased at a rate 40% faster than the population growth since 1950 (United States Department of Agriculture, 2017). Increased need for space is due to our appetite for the automobile.

Today the average American spends 733 hours each year in a car, and they are the primary mode of transportation for over 87.5% of Americans (AAA, 2015). The single connection between our mode of transportation and our destination then, is parking. Parking is the connective tissue between where we are going and how we get there. It is at the beginning and end of every trip and yet it is the most unpleasant of experiences as 30% of all traffic generated is from motorists looking for parking (Shoup, 2005). It is the single largest way in which automobiles and buildings interact.

History of Parking
The earliest parking spaces were originally curbside. The proliferation of individual car ownership, meant a reduction in linear space across streets. In 1923, Columbus Ohio became the first American city to codify parking regulation as part of a zoning ordinance for multi-family (LeCraw & Smith, 1947). In 1926, a nationwide survey of downtown merchants listed traffic congestion as their most serious issue (Jakle, 2004; Shoup 2005). Cities began to require and codify off-street parking standards and limit on-street parking. The first parking meter for on-street parking was installed in Oklahoma City in 1935¹. This pushed private landowners to begin to develop purpose-built parking garages as stand-alone structures or as part of larger commercial developments. By 1946 a survey of 76 US cities found that only 17 percent of municipalities had parking ordinances. Within 5 years, 71 percent had or were in the process of adopting them (Shoup, 2005). By 1949, 185 cities had adopted minimum parking standards (Jakle, 2004) By the 1970s, 95% of cities with more than 25,000 residents had adopted parking requirements (Ison and Mulley, 2014). Minimum parking requirements combined with escalating car ownership has seen a massive allocation of built space to parking.

¹ Ironically, this is the same year Monopoly was patented with its iconic “free parking” space.
Parking Estimates

In 2010, San Francisco became the first American city to attempt a census of its parking but limited the study to on-street spaces only. Cities require different numbers of parking spaces per each classification of land use, but few (Shoup 2015) said none have an exact data on the total parking supply. Average parking ratios fall between 3 to 4 spaces per 1,000 sf of building floor area (Ison & Mulley 2014; Ferguson, 2004). The ratio may seem low at first, but minimum parking requirements often require more square footage of (surface) parking than building area that it applies to. The basic parking dimensions of 9'x18' stall and a 24' width drive aisle mean that 1000 sf of building requires more than 1,080 sf of parking area. In Houston today, a 1,000 sf restaurant requires 1,300 sf of parking (Slate).

Parking ratios are often set as minimums and scale with the size of the building (Ferguson, 2004). It is now estimated between 3.3 parking spaces per vehicle (Chester et al., 2015). This estimate varies widely as it is difficult to ascertain the parking in private areas like single family home garages, in driveways, or even along streets that are not properly marked or measured. Chester et al. (2015) estimates the number of parking spaces in the US is between 800 million to 2 billion in a temporal and spatial analysis of Los Angeles. At an average of 350 square feet per parking spot, that is roughly the size of the size of Connecticut as a conservative estimate, or the state of West Virginia on the upper end. In his book “ReThinking a Lot” (2012), Eran Ben-Joseph notes “some US cities, parking lots cover more than a third of the land area, becoming the single most salient landscape feature of our built environment.”

Cost of Parking

The cost of parking can be measured through direct construction costs and indirect costs. The cost of construction ranges based on the context from as little as $7,000 per asphalted space and up to $36,000 per structured space (Carl Walker, 2016; RLB, 2017). Those hard cost estimates do not include soft costs or land costs which can be significant depending on the location. Shoup (2005) estimates that parking can account for 10% of the cost of a new building (Litman, 2017). Construction costs of parking are difficult to recapture as it is estimated that 99% of all vehicle trips in the US end with free parking (Shoup, 2005). Often this parking is a free amenity for retail shoppers, office workers, or apartment dwellers. The cost of parking is externalized to these users not through direct fees, but through the cost of other goods, services, and building uses. Manville (2013) describes this phenomenon from the end user to the up-front construction. Thus, the high cost of parking construction and minimum parking requirements have led to a highly standardized, ubiquitous land use.

The indirect costs of parking include increased greenhouse gases, increased suburban sprawl, and a decline in housing affordability. A study commissioned by Portland, Oregon (Portland Bureau of Planning and Sustainability, 2012) found that parking can increase the cost of housing by 19% for structured spaces, 50% for surface spaces, and 62.5% for underground spaces. A 2016 article by Bloomberg, found that from 1992 to 2015 the US has built more 3-car garages than 1-bedroom apartments (Clark, 2016). In a country facing housing shortages and an increasingly urbanized population, the competition for space will only continue to increase forcing new developments to demand higher rents or find ways to reduce parking costs or increase capacity.

5“When local governments require on site parking for new housing, the cost of housing rises and the price of driving falls. The cost of parking, which drivers should arguably pay at the end of their trips, is instead paid by developers at the start of their projects. The terminal cost of driving becomes an up-front cost of property development.” (Manville, 2013, p.49).
Figure 3. Parking construction costs by type and city. (Walker Parking, 2016; RLB Construction, 2017)

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HIT THE DECK - 15
A Brief History of Buildings for Cars

4. Park-itecture: a Search for Efficiency

Parking garages are among the most formulaic of buildings. Other categories of real estate have exterior and interior spaces that are expressed as different shapes, heights, and means of entry. But the parking garage has been reduced to its most basic unit of construction, the parking space, because of the reduction of vehicle manufacturers, the standardization of vehicle sizes, and stringent dimensional building codes. Using this single building block, garages are designed from the inside out. Rising construction costs, demand for urban land, increased building regulation, advances in building materials, and minimum parking standards have led us to seek greater efficiency from this necessary accessory to new development. The race to simplify parking structures has made typologies increasingly uniform. The quest for efficiency can be found in the material construction, design and layout, as well as mechanization and technology.

Construction and Materials

The earliest parking garages were about as rudimentary as the first automobiles: convenient, novel, yet lacking in critical functions. Original automobile designs were open to the elements. People would wear special coats, goggles, and garb for the pleasure of driving. Thus, one of the first questions to be addressed in the age of the automobile was where it would be stored. The word “garage” can be traced to the French verb gaer, which means to dock or shelter as a horse in a stable. Early on, vehicles were stored in barns alongside horses and there were even some early elevator ideas that would store a car above a horse’s stall (McShane & Tarr, 2007, p.109). Hence, “stall” became a North American name for a parking space. Since then, parking has come a long way since putting internal combustion machines in wood framed buildings filled with dry hay and animals.

In the transition from horse-powered to horsepower, buildings and stables were repurposed into car parks. Following the trends of economic prosperity, increased vehicular ownership, and stricter fire code requirements, purpose-built garages became popular buildings around the turn of the century. The first parking garage in the US were built in New York City in 1898. These structures were constructed much like any other building of the time out of local materials including wood, steel, stone, terracotta, or concrete, often multiple stories with highly stylised exterior elevations (McDonald, 2007). The most common form of parking garage construction in the first half of the 20th century was cast in place concrete with steel reinforcement. Some were built with steel depending on the locality and availability of materials, but steel poses problems with exposure to chemicals and weather. Even with the advent of reinforced concrete that became the norm for parking garage construction, structural limitations of early multi-story car parks meant the maximum distance was about 21 between columns (McDonald, 2007, p. 144).

By the 1940s longer spans and new layouts were made possible with the combination of new concrete mixtures, innovative structural shapes, and alternative reinforcement techniques. Additives to the concrete mixing process made the material more durable to the elements and road salts as well as helped it cure more quickly and become lighter weight. Precast, prestressed concrete sped up the construction process as the building components were poured separately and then assembled. The factory-controlled environment of precast ensures better quality in a controlled setting but a longer lead time. New structural shapes like the double tee, first used in 1961, drastically increased spans. Finally, post-tensioned (PT) concrete, invented in 1962, involved pouring the concrete forms around steel tendons that were tightened as the concrete cured. This provided better durability by producing flatter ceilings, more even weight distribution, and less cracking. This progression of construction techniques yielded spans three to five times longer (McDonald, 2007, p. ___).
146) and allowed for greater creativity, flexibility, and efficiency of parking space layouts.

Parking garages today are made almost exclusively of precast or PT concrete, but the architectural treatments, mechanical systems, and user interfaces vary greatly. Both Carl Walker publish a construction index in an attempt to standardize costs of parking garages across 28 US cities by assigning some minimum and median design requirements (Cudney, 2017). For instance, a garage must have a minimum height of 8'2" and parking space width between 8'6" and 9'0" wide. It is assumed that the garage is built above ground, with natural ventilation, shallow footings, pedestrian elevator, fluorescent lighting, and a basic exposed finish to the concrete without any additional cladding. The median hard cost for this standard type of parking garage is $19,700 per space or $59.06 per square foot. Higher costs are reported in Rider Levett Bucknall's quarterly report of construction values, which include parking but are limited to only 12 metropolitan areas in the US. (Rider Levett Bucknall, 2017). The construction index serves as a good baseline for parking garage construction typologies today.

**Ramped Parking**

D’Humy Ramp Garage pictures in Figure 4, patented in 1918, is a staggered, split-level garage with a pair of two-lane ramps at an 8% slope. An early example is the 10-story Book Tower Garage built in 1927 in Detroit (McDonald, 2007, p. 33). It increased sight-lines, travel speeds, eliminated the need for an elevator and reduced the length of the ramp. The helical ramp was also a popular design first released by Holabird and Roche in 1919. In 1922, continuously ramped garages made their debut in the Fort Shelby Garage in Detroit. The reduced incline of only 4% allowed for continuous traffic movement and for cars to be parked on the ramp itself. It is a continuation of the staggered level pioneered by the D’Humy ramp.

Figure 4. The D’Humy ramp system original design. (Library of Congress.)

Optimal parking garage layout standards were published as early as 1927 but went through a slow period of development in the 1930s following the Great Depression. A move toward efficiency yielded design and operational solutions. Open-air parking decks were a cheaper and more efficient way to build garages now that automobiles had enclosed cabs, durable finishes, and fluids that wouldn't freeze in winter. This removed the need for costly ventilation systems. The first open-air deck was designed by Coolidge, Shepley, Bulfinch, and Abbott in 1933 for Boston's 3-story Cage Garage (McDonald, 2007). Another move toward efficiency was the removal of attendants and valets in favor of self-parking. Patrons could remain in control of their cars the whole time and no time or money was spent on an
attendant. That meant that people began to have access to all of the garage floors and elevators were used to move humans and not cars.

The latter half of the 20th century saw rising land and construction costs as well as advancements in concrete construction. The earliest designs were the product of maintaining parks and open space at the ground level such as Philadelphia's mixed use project, Garden Court Garage in 1926 or San Francisco's Union Square in 1942 that preserved the plaza above (McDonald, 2007). With the aesthetic and spatial benefits of increased open space, came the challenges of waterproofing, ventilation, and increased structural loads to hold up the building and hold out the dirt. Underground garages gained prevalence with advances in concrete construction and the post-war boom but were generally reserved for space-constrained locations or to preserve open space. Now underground parking garages are common if not necessary in some urban settings.

Machine Parking

The third type of efficiency measure that can be found in parking garages is mechanization and computerization. Even for the most antiquated of vehicles, external automation can help boost efficiency in parking garages and reduce emissions. Versions of automated parking mechanisms have existed for over 100 years including elevators, turnstiles, and moving pallets that were originally activated by pulleys and horses (Munn, 2009). But there is a notable difference between automated, which relies on technology to move the car but still requires human interaction, and fully autonomous which doesn't require a human driver, nor system operator. Further differentiation should be made between technology that is integrated with a parking building/structure and automation that is a separate, mobile machine.

Mechanical and Automated Structures

Mechanical parking technology has naturally followed the same innovation, acceleration and plateau of other industrial technology cycles. The first industrial revolution of the 20th century saw creativity with mechanical advancements, and we've seen another spurt of creativity with technological advancements in the 21st. But this approach also faces challenges in construction costs, operational costs, retrieval time, and mechanical malfunctions.

In the early days of commercial parking garages, elevators, turnstiles, and sliding transfer platforms were used to maneuver cars inside buildings. Designs borrowed mechanization techniques from the industrial process and adapted them in creative ways to nascent automobile culture. The earliest automated parking system was designed by Parisian architect Auguste Perret in 1905 (McDonald, 2007). Early designs incorporated a central, vertical elevator shaft and turnstile where jockeys could maneuver cars from the lift into spots reducing the need for aisles or ramps. However, this design was dependent on a valet model and did not alleviate the need for passenger elevators or stairs for the jockeys.

Later in the 1920s, a Ferris wheel approach emerged that allowed circular rotation of platforms upon which cars could be parked and retrieved without an valet. Ramped designs still dominated the period throughout 1930s the 1950s. Following WWII, two popular variations on the theme of shafts and shelves developed on both coasts using a two-directional elevator. The east-coast Bowser model had a diagonal moving elevation which moved cars through the structure in one direction. The west coast Pigeon Hole model involved mechanical dollies, a vertical elevator, and horizontal track to move the dolly to each parking space. It was considered fully automated as attendants didn't drive the cars instead operated the system through a series of levers from a central location. The next step of automated parking was to computerize the controls which was pioneered with the first automated, computerized parking garage in 1984 in St. Louis (McDonald, 2007).
With improvements in computer technology, some garages use sensors, cameras, and scanners to automate the movement of cars throughout the structure. Historically, land constraints and construction costs must be high to justify this technological solution which is perceived to be costly, time-consuming, and difficult to maintain. However, fully-automated parking facilities have seen a renaissance in the early part of the 20th century with an increased urbanization and higher land costs. The first robotic parking garage was in Hoboken, NJ in 2002 ("Robotic Parking Systems - Projects", 2017). Although the first project, experienced difficulty with malfunctions, this sector of the industry has found some traction. As of 2012, there were over 6,000 robotic parking spaces in the US (Monahan, 2012)

Robotic and Autonomous Parking
The autonomous parking landscape began to take shape in the 1990s and has a new twist in the past 10 years: robots that can move cars and cars that are robots. The first type of robotic autonomy is not has found lift off with airports. “Ray” the robot, produced by Serva Transport Systems, has been in use at the Dusseldorf airport in Germany since 2014. Stanley Robotics has also been parking cars at the Charles de Gaulle airport in Paris since May 25, 2017, with their robot “Stan” (Dillet, 2017). This bot is equipped with sensors and hydraulic jack that can scan, lift, and precisely place each car. Travelers book a parking space online or via an app, park their car at the entrance to the airport, lock it, and leave. It is safer because no one enters the car, cheaper as the car can be parked at the fringe, cleaner (zero emissions) as the robots are electric, and more efficient as cars can be stacked up to 5 deep and in order of arrivals. This robotic valet means up to a 50% increase in parking space efficiency, reduced operating costs, and no required renovations to the structure ("Stanley Robotics - Operators", 2017).
Internet of Parking

As robotic parking increases spatial efficiency, IoT technology will increase the information efficiency parking garage from the inside out. Connected parking garages utilize wireless communication, sensors, cameras, and data analytics to streamline the customer and operator experience. This approach, otherwise known as "smart parking", has three main processes that help streamline operations: 1) determine space inventory, 2) connect to patrons, and 3) manage payment.

There are two main ways to detect occupancy is through either vision or sensing (Mustaffa, 2016). In the first, a digital camera is placed in an optimal perspective to monitor many stalls at once as well as count the number of cars. It records and optimizes the image input for changes in lighting, location of cars, and distortion. It is an affordable way to glean parking information but is not the most accurate when perceiving car counts or placements. The second method employs the use of a variety of different types of sensors including a magnetometer (usually below the parking space) or ultrasonic sensors (above the space) to determine occupancy. Although these sensors are more accurate, they can be costly to install, and their market penetration is minimal. In parking facilities with on-site staff this inventory is usually done manually by the attendant at various times throughout the day.

The second and third pillars of smart parking are closely tied together. Technology companies provide a vital service by connecting the physical structure and the digital customer and even offering payment platforms. Parking inventory counts are run through an API and can be input through the sensor data or manually. The API provider can then agglomerate parking availability and market available spaces to users through web-based or smartphone applications. This allows motorists with real time inventory, the ability to plan trips, and painless payment through an app. Providers may list their property and are charged a fee usually based on transaction. This service opens up broader audiences to operators, allows dynamic pricing, and a broader customer base. Third party parking app providers were among the first to fill this market although parking operators with large portfolios have come to design their own APIs. Not all parking apps include a payment feature, like Waze which has a dynamic map layer indicating parking areas and location, but it is a logical extension of the information.

5. Parking as Investment: the Forgotten Category of Commercial Real Estate

Parking Sectors

Because parking is a ubiquitous land use, it takes on many physical forms and various sectors. There are several key markets within this industry have their own unique location, typology, demand, and financial implications. Central Business Districts (CBDs) represent 45.5% of parking revenues and the largest sector in the industry (Rivera, 2016). This includes both public and private lots and garages but can be characterized by a higher revenue per space and a greater likelihood of structured parking based on land value premiums in urban areas. The second locational demand for parking is near airports, which make up 24.5% of all parking industry revenues. On-site airport parking typically is housed in parking garages while nearby providers with surface lots offer shuttle services. The revenue per space near airports is among the highest in the industry but can suffer from the same cyclical of air travel demand. Educational parking is the next largest sector of parking with 14.2% of the revenue, but with the lowest average revenue per space. Universities and Colleges manage large portfolios of parking of which 27% is structured. Hotels are another major market for parking with 10.3% of the revenue and the highest

6 According to Wesselt (2017) "smart parking is a strategy that combines technology and human innovation in an effort to use as few resources as possible—such as fuel, time and space—to achieve faster, easier and denser parking of vehicles for the majority of time they remain idle."
average revenue per stall and the greatest volatility. The smallest but most steady sector is healthcare and hospital facilities with 5.5% of the overall revenue.

**Parking Management**

There are a variety of different approaches to parking operations and can include any combination of direct ownership and management, third party management, or third party leasehold. Under a management contract, the parking operator receives a fee for managing the facility. These contracts can be structured a number of different ways including fixed fee, cost-plus, and performance-based agreements. Facility operators may charge fees for additional services such as accounting, equipment leasing, or consulting. The facility owner is usually responsible for operating expenses associated with the facility's operation. These expenses include taxes, license and permit fees, insurance costs, payroll and accounts receivable processing and wages of personnel assigned to the facility. Under a management contract, the property owner is usually responsible for capital improvements, such as structural repairs or system upgrades. Management contracts range from a term of one to three years.

Under a parking facility leasehold, the operating company generally pays the property owner a fixed base rent, percentage rent that is tied to the facility's financial performance, or a combination of both. The parking facility operator collects all revenue and is responsible for most operating expenses, but typically is not responsible for major maintenance, capital expenditures or real estate taxes. In contrast to management contracts, leases typically are for terms of three to ten years, often contain a renewal term, and provide for a fixed payment to the facility owner regardless of the facility’s operating earnings. Many of these leases may be canceled by the client for various reasons, including development of the real estate for other uses and other leases may be canceled by the client on as little as 30 days’ notice without cause. Leased facilities generally require larger capital investment by the parking facility operator than do managed facilities and therefore tend to have longer contract periods.

Ownership of parking facilities, either independently or through joint ventures entails greater potential risks and rewards than either managed or leased facilities. All owned facility revenue flows directly to the owner, and the owner has the potential to realize benefits of appreciation in the value of the underlying real estate. Ownership of parking facilities usually requires large capital investments, and the owner is responsible for all, mechanical and electrical maintenance and repairs and property taxes.

**Parking Investment**

Parking is typically not treated as its own real estate asset class because it is typically built to support other uses. Despite the lack of traditional long term-leases, parking assets can be quite valuable. Parking is usually valued one of three ways: a stand-alone asset class with recurring demand and low expenses, a land bank purchase that produces minimal returns, or as a necessity to support another real estate use category with little to no value on its own.

Well-sited parking garages can drive returns through complimentary surrounding uses. In areas with high parking demand, the demand for other real estate uses is likely high as well, and could then a likelihood of higher rents and returns. But the attractiveness of a parking asset is the minimal labor, maintenance, and capital expenditure costs. The average useful life of a parking garage is from 30-40 years (Shiu & Stanish, 2011) with very little capital intensity, an average of $.03 for every dollar spent on wages (Rivera, 2016). However, competition is high in the industry with volatility of cash flows are medium to high depending on the location.

Institutional investment in parking is not a typical, as the unpredictable cash flows are a deterrent for most risk-averse investors. However, in a competitive market, investors must look at niche/alternative assets for looking for higher returns as prices for traditional assets are at
Real Capital Analytics lists 60 parking facility trades in 2017 to date, the highest of any complete year in its transaction database (Real Capital Analytics, 2017). However, RCA is among very companies that track parking garage trades, and there is a scarcity of parking investment information and most commercial real estate data providers and listing companies (LoopNet) don’t even list parking as a property type.

Perhaps the most valuable aspect of parking is its ability to be redeveloped for another use. It would be rare for a commercial real estate appraisal to return parking as the result of a ‘highest and best use.’ Instead, parking can be looked at as an investment in a land option, whether or not the parking use yields any profit, although most do. Geltner, Miller, and Brown (1994) found that although real returns were a minimal 3-8%, the appreciation return on the land value for these CBD-located parking lots was an average of 48% increase in value over 12 years.

Perhaps this is why some of the highest per stall transaction costs more recently in the RCA database were north of $280,000 per space, more than ten times what it would cost to build a parking garage. This is because the some of the highest trading garages were purchased with another use in mind, whether it be a redevelopment or a new building, and have actively been pursuing those options. Other high parking transactions are consistently hotels and airports. However, on-site airport providers must content with the airport authority and their access to public bonds and low-interest capital.

Parking Players

There are approximately 12,896 parking facilities' in the United States (Census, 2015). Demand projections by the National Parking Association state revenue is projected to grow from just under $25 billion in 2015 to nearly $29 billion by 2018 (NPA, 2016). This market is highly segmented with the largest three companies holding only 31.2% of the market share. Most facilities are privately held, and owners can be categorized as individual, often family-run operations; large conglomerates of publicly traded-companies; small niche real estate firms; and few institutional real estate investors.

Of the handful of publicly traded parking companies, the most notable are SP Plus, ABM, and 24 Park. SP Plus is a conglomerate of Standard Parking and Central parking that merged in 2012 who manages over 2 million parking spaces over 3,686 properties in 46 states and also operates airport shuttle services (Rivera, 2016). ABM Services has 1,800 parking operations in 39 states and 6.5% of the market (Rivera, 2016). Park24, a Japanese based parking company that manages 670,485 spaces over 17,930 properties and also deals in car rentals (Park24, 2016). Indigo, part of French company Infra Park, has acquired notable parking businesses (LAZ) in the US and is one of the most technologically advanced parking operators in the US with over 2,200 properties, 845,000 spaces in 300 cities (Infra Park, 2017).

There is only one parking REIT in the US, and that is MVP, formed in 2013 and active in 13 states. However, a recent IRS ruling may increase interest in this sector for public companies as it decided parking cash flows are treated as qualifying income from property rental. Recently, TIAA Private Investments and Antarctica Capital of New York City acquired parking operator InterPark, a company valued at $1 Billion (Bubney, 2017). InterPark has holdings in 13 core urban markets in the US with eight airport locations.

In addition to the traditional owners and operators, a new sector of parking business has emerged in the last decade as technology companies have joined the industry. With the adoption of the smart phone, parking has gone mobile and the industry has seen significant

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2 Construction, purchase, maintenance, and operation of public-use parking lots, garages, parking meters, and other distinctive parking facilities on a commercial basis.
investments being made in parking technology that assist both the customer and the operator with real-time information. Services provided in this sector include mobile reservation and payment, self-listing sites, data analytics, on-demand valet (Index.co, 2017). Other technology companies are investing in parking at the car level and will be discussed in subsequent sections.

Parking reservation apps are third party booking platforms that agglomerate parking availability either on or off-street, monthly or hourly, and market available spaces online or via mobile devices. Providers may list their property and are charged a fee usually based on transaction. This allows motorists with real time inventory, the ability to plan trips, and painless payment through the app. This service opens up broader audiences to operators, allows dynamic pricing, and a broader customer base. Other booking platforms allow individuals to list their private property as parking spaces in a way much like Airbnb.

Data providers offer platforms for providers optimize parking assets through analytics, big data, and dynamic pricing. They provide greater interaction between facility operators with consumers and the rest of the parking market. Originally geared toward owners and operators, some companies have started to offer reservation services as well.

On-demand valet services are a combination of a chauffeur, valet, and on-demand transportation. They provide car owners with the ability to request a drop-off or pick up of their own car by valet at any time. This subscription-based service is an interesting step towards a virtual valet that autonomous vehicles can offer, but fills the gap between current private car ownership and autonomous vehicle parking.
A Brief History of Autonomous Vehicles

6. The Long Road of Autonomous Vehicle Development

History
Before there were driverless cars, there were driverless carts. Da Vinci's famous Codex Atlanticus folio featured a self-propelled cart that could be wound up via springs, steering “programmed” with pegs, and even had a remotely controlled handbrake. Although it was originally intended for theater, it would take centuries for us to reinvent this kind of drama.

In 1925, Houdina Radio Control company paraded a driverless 1926 Chandler down the rush hour streets of New York City. The “Linrrican Wonder” was controlled via radio signals and a series of small motors similar to Archen Motor’s “Phantom Auto” a year later in Milwaukee. A decade later in New York, GM sponsored an exhibit designed by Norman Bel Geddes titled “Futurama” at the 1939 World’s Fair. His exhibit depicted electromagnetic fields embedded in a trench-like track that would propel radio-controlled electric vehicles. The exhibit was more about a smart road than a smart car, but it captured the imagination of America and promised “These cars of 1960 and the highways on which they drive will have in them devices which will correct the faults of human beings as drivers” (Kröger, 2017).

Although the original deadline came and went, GM and RCA labs continued research efforts on driverless throughout the 1950s and 60s with a 400’ successful smart highway prototype in New Jersey. In 1961, Stanford built the first radio-controlled camera bot to develop a moon-walking vehicle. But in 1962, a manned moon mission was announced, and the Stanford Cart research was reappropriated. Back on earth, cruise control was invented in 1968 by RCA and that same year seat belts were federally mandated. Research continued quietly in US locations such as University of Illinois and Stanford, but the 70s saw the most progress in the UK, Germany, and France with varying degrees of successful semi-autonomous trials in each country.

The first self-guided (e.g. without a smart road or remote driver) cars appeared in the 1980s (Navlab, 1984). The Defense Advanced Research Projects Agency (DARPA) became a catalyst for research with their Autonomous Land Vehicle (ALV) program that launched in 1985. Within 9 months, it released their first autonomous vehicle with lidar, computer vision, and robotic control technologies developed from research universities and the private sector. Carnegie Mellon’s NavLab, founded in 1984, began testing its first vehicle (a Chevy panel van) in 1986. They became a pioneer in using neural networks to program the navigation of autonomous vehicles. (Mercedes-Benz and Bundeswehr University Munich’s Eureka Prometheus Project in 1987). Also in 1986, the Program for Advanced Transit and Highways was founded at the University of California, Berkeley. A notable milestone was that of the PATH program launched in California that successfully drove 8 automated vehicles at 60 MPH speeds in a connected line, called platooning, using magnets and radio remote controls that connected the cars to one another and to the road.

The US formally instituted a policy on driverless vehicles with its ISTE A transportation bill of 1991. The legislation gave the USDOT a mandate to “demonstrate an automated vehicle and highway system by 1997”. The project became officially known as the National Automated Highway System Consortium (NAHSC) and included private companies, federal administrations, and public universities (FHWA, General Motors, Caltrans, Delco, Parsons Brinckerhoff, Bechtel, Lockheed Martin, UC Berkeley, Carnegie Mellon University). As scheduled, a demonstration took place in 1997 with 20+ vehicles traveling individually and in platoons down Interstate 15. Although the project was canceled shortly thereafter, the seed was planted and autonomous vehicle research began to spread.
In 2001, in an effort to preserve the lives of military members, U.S. Congress mandated that one-third of the operational ground combat vehicles drive unmanned by 2015. These vehicles could be used to transport cargo, supplies, or provide surveillance. DARPA was tasked to lead this effort and the federal entity again re-entered the world of automation and used an unconventional approach. They established the prize-based DARPA Grand Challenge competition that would invite teams to compete in an on road autonomous vehicle challenge. It began in 2004 with 15 qualifying teams and its first $1 million challenge grant, which no team won. In 2005, 195 teams applied and five teams completed the challenge with Stanford in first and Carnegie Mellon in second. The third and final DARPA challenge was held in 2007 in an urban environment and this time Mellon placed first. These competitions were instrumental in creating the private, public, and educational partnerships that accelerated the development of autonomous technology.

Since DARPA’s initial success in 2005, mainstream automakers and other seemingly unlikely technology companies began to fund, study, and test autonomous technologies on a much greater scale. Google began development on its well-known program in 2009 but didn’t publicize the first prototype until hitting private roads in Nevada in 2012 and has since driven over 2 million miles in 4 cities. Tesla, notably headed by tech and engineering magnate Elon Musk, released their first “Autopilot” tech package in 2014 in partnership with Israeli company Mobileye. Since 2014, Tesla says they have amassed 1.3 billion miles of Autopilot driving data.

Legislation
Cumulatively, companies have tested nearly 3 million driverless miles in the US all without a single piece of federal regulation. The NHTSA published a preliminary policy statement in 2013 with an official guidance published in 2016 after it was given a federal mandate to fund autonomous research as part of the 2015 Surface and Transportation Act. (NHTSA, 2016) Following the legislation, US Secretary of Transportation, Anthony Foxx, announced $4 billion in autonomous vehicle research funding over a period of 10 years at the 2016 North American Auto Show in Detroit, Michigan. In 2017, Foxx made another announcement that designated 10 testing areas for AV’s in nine states: CA, FL, IA, MD, MI, NC, PA, TX, WI (USDOT, 2017). Since then, Secretary Foxx was replaced by Elaine Chao with the new administration in 2017. Although continued government funding is always uncertain, it appears that Secretary Chao will continue to explore autonomous vehicle policy and research.

As of July 2017, 41 states have considered legislation regarding autonomous vehicles. Nineteen states have passed legislation while four more have issued executive orders to address driverless vehicles. The first state to allow autonomous vehicle testing was Nevada in 2011. The following states shown in Figure 7, have enacted legislating pertaining to autonomous vehicles. However, only 5 states have active autonomous vehicle testing. The House and Senate are both actively pursuing draft legislation. As of July 19, 2017 a House Energy and Commerce subcommittee approved a bill titled the “Highly Automated Vehicle Testing and Deployment Act of 2017”, that establishes a framework for autonomous vehicles (Roose, 2017). This bill would allow for the deployment of 100,000 autonomous test vehicles that do not have to meet federal safety regulations. Instead, they would submit reports to regulators but would not have to seek prior approval for the technology. The legislation may supersede states’ abilities to regulate driverless cars within their borders. The Senate is also pursuing similar draft legislation.
Figure 7. States with Enacted Autonomous Vehicle Legislation, National Conference of State Legislatures (NCSL).

The term “driverless” vehicles is generic and potentially misleading because it refers to a spectrum of automated technologies that can be individual or combined. The accepted standard for automation is published by the Society of Automotive Engineers and is broken down into six different levels as shown in Figure 8. For the purpose of this thesis, “autonomous vehicles” refers to Level 4 automation and above.

Figure 8. Society of Automotive Engineers’ 5 Levels of Autonomous Driving (GHSA, 2017)

Technology

There is a symphony of sensors that have come together in the last several decades to make autonomous vehicles possible. It is this recombinant innovation that make driverless technology so complex and collaborative. A driverless car needs not only to know its position...
and move through our transportation network but understand the world around it. It must be able to detect objects, perceive their meaning.

To put it simply, an autonomous vehicle must know where it is going, see where it is going, and get where it is going. This helps us put the smorgasbord of sensors into three rough categories: 1) self perception, 2) external perception, and 3) communication. This section will explore the technology associated with each of these different categories.

Figure 9. Autonomous vehicle technology suite. (Reuters, 2016)

**How self-driving cars see the road**

Autonomous vehicles rely on a host of sensors to plot their trajectory and avoid accidents.

- **Multi-domain controller**
  
  Manages inputs from camera, radar, and LiDAR. With mapping and navigation data, it can confirm decisions in multiple ways.

- **Camera**
  
  Takes images of the road that are interpreted by a computer. Limited by what the camera can "see".

- **Radar**
  
  Radio waves are sent out and bounced off objects. Can work in all weather but cannot differentiate objects.

- **LiDAR**
  
  Light pulses are sent out and reflected off objects. Can define lines on the road and works in the dark.

**Self Perception**

**Global Positioning System/GNSS**

Although satellite technology dates back to the 1960s, GPS was fully functional and available to the public in 1995. Since then, the technology has dropped dramatically in price (less than $5) and is embedded in everything from your phone, laptop, car keys, or pet. GPS computes position from signals received from a constellation of over 60 low-orbit satellites circling the earth. Each satellite has its own unique microwave signal which can be used to determine location, time, and velocity through triangulation calculation. A receiver only needs signals from four of these satellites to determine a location accurate to 1 meter. However, GPS is not perfect and the signal can be blocked or interrupted by technological or physical structures.

GPS is a large component of the locational perception of driverless vehicles, although the unit itself is quite small. The chip, or integrated circuit (IC), can be as small as 15mm x 13mm as the one pictured by Mouser Electronics below, and requires only power and an antenna. The antenna must match the polarization of the GPS signals and can be physically manifested in a number of different ways. A low-noise amplifier for the 1.5GHz signal can be built into the chip or separately manifest on the car similar to the antenna. The chip computes location from GPS received signals and outputs data to the car’s computer processor via serial interface (SI) in the industry-standard...
National Marine Electronics Association (NMEA) message format. An SI is communication interface between two digital systems that transmits data as a series of voltage pulses down a wire. This triangulation can be instantaneous or can take up to 30 to 60 seconds to calculate. To assist in more accurate positioning, the autonomous vehicle needs further locational technology assistance.

Figure 10. Linux GPS Module - RXM-GPS-F4-T (Mouser Electronics, 2017)

Notable Manufacturers: TomTom, Point One, Swift, Qualcomm, NovAtel

Inertial Measurement Unit
An inertial measurement unit is a collection of sensors that are installed in a vehicle that provide proprioceptive position. The technology provides a sense of balance, direction, and velocity using a dead reckoning navigation calculation. Developed for military purposes during WWII, the relentless advances of technology has reduced the size and cost of IMU's that now exist in every smartphone.

This collection of sensors is also relatively small and is affixed to a platform or roof on the vehicle as shown below in Figure 11. The platform includes a compass, odometer, and 3 sets of gyroscopes and accelerometers for each axis, X, Y, and Z, that collect rotational and velocity data. These sensors collect data on the vehicle and sends it to the central processor which calculates the speed, direction, and movement of the vehicle. An IMU cannot determine your exact position, only the motion, so the starting point of the vehicle must be determined by GPS or entered manually (Mouser.com "A Diverse Array of Sensors", 2017). An IMU is a powerful tool in maintaining the balance and safety of an autonomous vehicle, but it must work in tandem with GPS.

Figure 11. IMU04 with roof mount (VBOX, 2016)

Notable Manufacturers: VBox, KVH, Advanced Navigation, Race Technologies,

External Perception
Much of the attention of autonomous vehicle technology has been focused on the hardware that allows the car to "see" and sense its surroundings. A combination of technologies has been employed to replace and enhance the eyes and ears of a driver. But these
technologies simply gather data and still require a brain, or central computer, to analyze the signals and develop a protocol based on the inputs.

Cameras
High definition cameras are the most like human eyes in that they can only process one viewpoint at a time. The light gathered by the camera lens is absorbed as photons and converted to electrical pulses via a silicon receptor similar to our retinas. But cameras represent context via pixels instead of neural signals. Pixels are simply a collection of numbers mapped out on the grid array of the receptor.

High definition cameras are the cheapest way to generate an image of the surrounding environment. Twenty years ago, a one megapixel camera was considered advanced. Now there are gigapixel cameras and terapixel images not far away. An exponential increase in pixel details makes data from cameras more complex to discern. Apart from the data processing, cameras present other issues with 1) physical constraints of aligning, focusing, and keeping the lens clean, 2) clarity of images in different lighting and climates, 3) the processing power needed to interpret images, 4) depth perception. One advancement in depth perception is structured light cameras that have been deployed in video gaming settings. These cameras project a grid onto an image and measure its distortion to determine depth perception. However, the drawback of these cameras is that they do not work in natural daylight settings with the intense infrared light of the sun and are only accurate up to 100 feet. Their application in autonomous vehicles is limited in its current form without significant refinement.

Despite some the digital processing and analog drawbacks of cameras, they are still the top choice for autonomous vehicle manufacturers. Most OEM's have opted to put multiple cameras on the car body to deal with the single point of view issue. Uber's technology suite shown in Figure 12 has 20 individual cameras. Tesla famously has proclaimed cameras are superior in imaging and lower in cost than other visualization technologies (Hoffman, 2016).

**Figure 12 & 13. Uber camera mount as part of technology suite for Ford Fusion (Flynn, 2016)**

Use: sign interpretation, detect traffic lights
Notable Manufacturers: Delphi, Mobileye, Panasonic, Denso

Lidar
Lidar (light detection and ranging) is a more robust version of imaging. It provides 3D information about surrounding environment using focused, high-frequency, short pulses of laser light that are timed with the response of a detector. The laser light bounces off of
surroundings to determine depth, form, and distance up to 100 meters. The reflections of the laser are then detected by the receiver and used to create a 3D image from thousands of point observations. The observations are then analyzed to transform the data into volumetric, material, and vector information. Lidar dates back to the 1960s and has been used for decades to create accurate land surveys of stationary settings. Its recent application to moving environments has caused the cost to be drastically reduced by 90% in just 3.5 years. The size and price of this technology are increasingly condensed as in the $5,000 unit from Velodyne shown in Figure 14, while competitor Quanergy promises a lidar package for a driverless car at a shocking $250.

Lidar scans and maps a 360 view of its surroundings and is great for longer distance imaging. But lidar is not without its own limitations. Unlike a full-spectrum light image of a camera, lidar cannot see color. And although their data is a lighter load for computer processing it takes longer to generate contours of the environment when compared to a near instantaneous capture of a camera. Lidar was instrumental in the DARPA challenge winners of the early 2000s, and despite the drastic cost reduction, it has fallen out of favor with some OEMs. Tesla’s CEO famously declared that he is “not a big fan of lidar” and would pursue instead a combination camera and radar on future Tesla models (Hoffman, 2016).

Figure 14. Velodyne VLP-16 $5,000 (Velodyne LiDAR, 2017)

Notable Manufacturers: Mobileye, Velodyne, Quanergy, LeddarTech, Continental

Radar
Radar bounces radio waves off of objects to determine their location, angle, speed, and even direction of travel using the Doppler effect. Radar is reflective and can sense behind and around objects in its path. It must employ both long and short wavelengths to sense objects both near and far away. Radio waves are not dependent on light, and it can function well in low-visibility settings. It creates an echogram of images with fewer data points for lighter weight processing than lidar or cameras.

However, radar is not as precise as lidar and tends to overlook smaller objects or ones that are made of less reflective material like wood or plastic. Its closely-related cousin, sonar, travels much slower and is better at detecting smaller obstacles but tends not to do well in wind. They have a limited point of view so multiple sensors are needed. Radar sensors, like the Bosch model shown in Figure 15, are inexpensive ($15-200) so three sensors to cover a 180-degree view is not cost prohibitive. It is built into bumpers and sides of car for close-in imaging and is currently used in the consumer car market in blind spot detection, adaptive cruise control calculations, and obstacle sensing in self-parking settings.
Computation and Communication

The lifeblood of the autonomous vehicle are the electrical pulses control, connect, and communicate the digital and physical worlds. These simple bits and bites of communication determine the fate of the vehicle and its car go. Technology is programming inorganic materials and networks to outperform something as complex as the human brain and it takes an immense amount of software, data, and processing power in order to even come close.

Processor

A PC-like computation device combs both computer processing units (CPUs) and graphical processing units (GPUs). This central computer will calculate and analyze sensor input, apply its programmed rules, and output actions for the various onboard systems. Basic functions will include data segmentation, object identification, collision prediction, route planning, and object avoidance strategies. All of this will take an immense amount of processing power and programming protocols. These protocols are communicated via to thousands of actuators translate the electromagnetic message to physical movements that control the car.

Cars today have about 100 different CPUs on board and run 300 million lines of code. They have the processing power of 20 personal computers and process 25 gigabytes of data every hour (McKinsey, 2014). Autonomous vehicles need to run about 300 billion lines of code to run autonomously. Between the hard and software, there is another line of technology called middleware (e.g. PolySync). This allows all the car systems to talk to one another and reduce the computers needed to run the car. The computational brain of the autonomous vehicle depends on the size and complexity of data provided to it. On average, the central processor will run about 50-200% the cost of the combined sensor package.

There is some debate on whether car companies will opt for proprietary operating systems or for open source. Each car company may write an operating system that will include a series of learned processes, formulas, and calculations called algorithms to navigate the built environment. Some driverless giants like Baidu are pushing for open-source platforms.
Figure 16. Intel Go Processing platform with Intel Xeon and Atom processors. (Intel, 2017)

Manufacturers: Nvidia (w/Tesla • Audi) and Intel (w/BMW)
Models: Go, Xeon, Tegra, Drive PX2
Use: object recognition, avoidance, prediction;

Machine Learning
Broadly speaking there are two types of artificial intelligence that together help to guide the autonomous vehicle. One is rule-based, and the other is outcome-based.

Rule based AI has defined robotics for decades. Rule-based learning requires an expertly labeled set of data or protocols so that a machine can either solve for the process or the original input. This approach stems from decades of thought including modern control theory, inductive and deductive reasoning, and rapid Heuristic optimization. This can be helpful for certain software functions like system controls, obeying traffic rules, or route planning. Rule-based intelligence is a top-down approach that must be expertly coded and is reasoning on a basic, structured level.

Data-driven AI, also known as machine learning, that has revolutionized autonomous tech. This is a bottom-up approach that begins with the input and works backward to identify it and forwards to make a plan. Machine learning involves applying an algorithm to large amounts of data and using statistical techniques to process that data. The algorithm, based on some human programmer oversight, defines the outcome and will validate the predictions and analysis of the data. This eventually exposes the patterns so that the machine “learns”. However, this is just the beginning of the deep learning needed for autonomous vehicles. It is impossible to give the sort of feedback and reinforcement needed for driverless cars as they will constantly encounter new settings and issues.

This is why some programmers and mathematicians have proposed End-to-End Learning. The E2E algorithm learns like a human with a single front facing dash camera for data input and an expert set of outcomes based on human behavior. It maps pixels to actuation and directly mimics the demonstrated performance. This is in stark contrast to CNN directly learning the mapping from pixels to actions. Less complex but perhaps more risky. Unsupervised learning is currently being pioneered by Cortica who would like to see autonomous vehicles map not only objects but gestures ("Cortica teaches autonomous vehicles", 2017).
Maps
Machine vision improves with every autonomous mile driven in the US, but vehicles are still dependent on digital maps for navigation. Highly detailed maps can take computing load off of the machine. By establishing an a priori framework of existing conditions, the car can then compute what has changed and what to do about it. This approach to navigation and mapping is called SLAM: Simultaneous Localization and Mapping. The car will keep track of its position while updating the system with new information. The mapping resolution needed for an autonomous vehicle is at the centimeter level and not the meter level. Autonomous vehicles need to know the height of the curb, the width of the road, and even the location of the pothole. In addition to the base layer of maps, there are also dynamic layers that will show changes in the environment from traffic, to construction cones, to idiosyncratic driver behavior.

One challenge with developing these maps is that they are incredibly time and cost intensive to establish. This means that the competition in this market is not as strong as other components of driverless cars although there is no clear leader and plenty of room for new players. The second challenge is being able to update the maps quickly and in real time. Autonomous vehicles will need a seamless, continuous stream of new and up to date data including information on where to park. In the future we could see mapping providers routing cars through aisles of a parking structure the same way they do for streets. This level of detail would be helpful inside concrete structures where GPS signals may be weak.

Some autonomous companies are investing more heavily in mapping technology than on sensors. Daimler, Audi, and BMW recently purchased Nokia’s mapping company HERE for $3.1 billion in 2016 despite the company having been in existence since 1985. Uber spent $500 million since 2016 launching a proprietary mapping system. Waymo has the benefit of Google Maps and Waze that despite only being created in 2005, have more miles mapped than any other provider.

Notable Companies: Here, Google, Uber, Mapbox, Baidu, TomTom, Google, Udacity
An Uncertain Future of Parking

7. Parking Predictions in an Autonomous Future

Although fully autonomous vehicles may not be available at the consumer level until 2020, certain types of automation are currently on the market and becoming increasingly prevalent. These types of automation are typically referred to as Advanced Driver Assistance Systems (ADAS) and ranked as SAE Level 2 automation. Examples include adaptive cruise control, lane keeping, and parking assistance. Consumer preference for parking assistance and limited driving capabilities has increased from 38% to 43% in a recent survey from Deloitte (2017). This is why some predict that the initial disruption of autonomous vehicles will be in the parking sector.

As of March 2017, ten auto manufacturers with over 40 models produce cars that have parking assistance, whereby the vehicle can control steering, direction, and velocity ("Which cars have self driving features", Cars.com). Tesla's "autopark" and "summon" feature, released Fall 2015 and now in its second iteration (Lambert, 2017), is a close approximation to fully-autonomous parking, where a driver does not need to be in the car, but it has a limited range of 40 feet. Recently, Daimler and Bosch debuted a fully autonomous valet service (see Figure 17 and 18) in a multi-level parking facility at Stuttgart's Mercedes-Benz museum (Autocar Professional, 2017). The forthcoming Audi 8 also claims to be able to have remote autonomous parking where the driver need not be in the vehicle.

"Autonomous parking will be ready long before autonomous driving," said Lawrence. "And cities are looking at this too, because 30 percent of traffic is caused by people not going anywhere but circling for a parking spot. Imagine if we could eliminate all of that because people knew exactly where they were going to go and how much they were going to pay." -Spot Hero
Currently available technology, increasing consumer adoption, and large parking space market, mean that small changes in autonomous vehicles could create large changes in the nationwide parking industry. There are several major trends related to autonomous vehicles that will have an impact on parking demand in the future. The first deals with the total number of cars on the road and the fraction of which are autonomous. The second trend addresses the cost of driving by autonomous or legacy vehicle and the resulting number of miles traveled. And the last is the relative efficiency in parking spaces triggered by autonomous vehicles and the resulting change in demand. The following meta analysis describes the research devoted to each of these trends and what that means for parking properties.

Market Penetration: cars on the road

The number of cars on the road is one of the key indicators for parking demand as automobiles currently sit idle 94-96% of the time (Shoup, 2005). One of the most frequently explored topics the number of both autonomous and legacy vehicles there will be and by when. If a private ownership model pervades, and the number of automobiles simply shifts from ICE to AV. Not much change will be experienced. However, prediction show significant changes expressed in three ways: the rate of new autonomous vehicle sales, the ratio of autonomous to legacy vehicles, and the absolute number of all vehicles on the road.

Fifteen different studies were surveyed for their potential impact on the automobile market. Sources on this topic are incredibly diverse and include banks, auto consortia, architects, academics, think tanks, and consulting groups. The publication years of these studies span years from 2013 to 2017 with the mean being 2015. The average absorption rate of autonomous vehicles as understood by new car sales is 38% of all new cars by the year 2043. The next question surrounding autonomous vehicles is the obsolescence of ICE vehicles and the total amount of cars left on the road. The ratio of autonomous vehicles as part of the total US fleet follows is a higher percentage/prediction than new car sales with the assumed efficiency of driverless cars being able to serve more functions and users. The fleet proportion is projected to be 55% by 2037 on average. Some authors have stated that one autonomous vehicle could replace 11 legacy vehicles (Kockelman & Fagnant, 2014) leaving the US with just 44 million cars in 2040. At the household level, a reduction of vehicles from 2.4 to 1.2 vehicles per household could mean the end of the two-car garage.

Figure 19. Percent Autonomous Vehicle in US Fleet Forecast

<table>
<thead>
<tr>
<th>Source</th>
<th>Published</th>
<th>AV vs. ICE</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morgan Stanley</td>
<td>2013</td>
<td>100%</td>
<td>2055</td>
</tr>
<tr>
<td>Lux research (Laslau et al.)</td>
<td>2014</td>
<td>8%</td>
<td>2030</td>
</tr>
<tr>
<td>Fehr &amp; Peers (Bierstedt et al.)</td>
<td>2014</td>
<td>25%</td>
<td>2035</td>
</tr>
<tr>
<td>IHS Automotive</td>
<td>2014</td>
<td>100%</td>
<td>2050</td>
</tr>
<tr>
<td>Litman</td>
<td>2015</td>
<td>30%</td>
<td>2040</td>
</tr>
<tr>
<td>Litman</td>
<td>2015</td>
<td>50%</td>
<td>2050</td>
</tr>
<tr>
<td>Rowe</td>
<td>2015</td>
<td>100%</td>
<td>2060</td>
</tr>
<tr>
<td>Kockelman</td>
<td>2016</td>
<td>25%</td>
<td>2045</td>
</tr>
<tr>
<td>Kockelman</td>
<td>2016</td>
<td>87%</td>
<td>2045</td>
</tr>
<tr>
<td>ReThinkX</td>
<td>2017</td>
<td>60%</td>
<td>2030</td>
</tr>
<tr>
<td>BCG</td>
<td>2017</td>
<td>25%</td>
<td>2035</td>
</tr>
<tr>
<td>Rocky Mountain Institute</td>
<td>2017</td>
<td>70%</td>
<td>2035</td>
</tr>
</tbody>
</table>
Figure 20. Autonomous Vehicle Sales Forecast as Percent of All New Sales

<table>
<thead>
<tr>
<th>Source</th>
<th>Published</th>
<th>% New Sales AV</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litman</td>
<td>2015</td>
<td>50%</td>
<td>2040</td>
</tr>
<tr>
<td>Litman</td>
<td>2015</td>
<td>90%</td>
<td>2050</td>
</tr>
<tr>
<td>Litman</td>
<td>2015</td>
<td>25%</td>
<td>2030</td>
</tr>
<tr>
<td>ABI Research</td>
<td>2013</td>
<td>50%</td>
<td>2032</td>
</tr>
<tr>
<td>BCG (Mosquet et al.)</td>
<td>2015</td>
<td>10%</td>
<td>2035</td>
</tr>
<tr>
<td>BCG</td>
<td>2017</td>
<td>13%</td>
<td>2025</td>
</tr>
<tr>
<td>BCG</td>
<td>2017</td>
<td>25%</td>
<td>2035</td>
</tr>
<tr>
<td>BCG</td>
<td>2017</td>
<td>43%</td>
<td>2040</td>
</tr>
<tr>
<td>Intel</td>
<td>2017</td>
<td>20%</td>
<td>2050</td>
</tr>
<tr>
<td>McKinsey</td>
<td>2016</td>
<td>15%</td>
<td>2030</td>
</tr>
<tr>
<td>McKinsey</td>
<td>2016</td>
<td>60%</td>
<td>2035</td>
</tr>
<tr>
<td>McKinsey</td>
<td>2016</td>
<td>90%</td>
<td>2040</td>
</tr>
<tr>
<td>Deloitte</td>
<td>2016</td>
<td>30%</td>
<td>2035</td>
</tr>
<tr>
<td>Deloitte</td>
<td>2016</td>
<td>70%</td>
<td>2035</td>
</tr>
<tr>
<td>Ernst &amp; Young</td>
<td>2015</td>
<td>41%</td>
<td>2030</td>
</tr>
<tr>
<td>Ernst &amp; Young</td>
<td>2015</td>
<td>75%</td>
<td>2035</td>
</tr>
</tbody>
</table>

Cost of Driving: dollars, miles, trips, and ownership

Demand is also related to the relative number of trips a car makes, as parking the beginning and end point of every voyage. The average driver in the US makes about 4.1 trips per day (Childress et al., 2015) and travels about 30 miles per day. A standard combustion engine vehicle will cost about $.97 per mile inclusive of all costs of owning and operating the vehicle. It is predicted that autonomous vehicles will decrease the cost of travel thereby increasing the number of miles traveled and trips taken. The average prediction for cost per mile in an autonomous vehicle varies greatly as each study makes specific assumptions about the nature of the trips, shared or individual, privately-owned or fleet-operated. The average cost per mile in an autonomous vehicle is $.23 by the year 2031. Some estimates forecast changes as early as 2021 at $.16 per mile or as conservative as $.29 by 2040. Studies have also been reviewed that did not offer a timeline for their estimates.

As the cost to travel falls, demand for travel naturally increases. The vast majority of studies predicted an increase in vehicle miles traveled (VMT). The average increase in VMT is -15% but varies greatly from 4% to 50%. One variation across these studies is the different ways in which travel behavior was modeled based on elasticity of time value, age, and preference. Some also assume specific geographies for their applications and capacity upgrades to transportation networks. In many cases, they also do not account for the timeline of increased VMT. For a closer look at when VMT may increase, I examined literature on the ratio of miles driven by VMT as opposed to a standard automobile.

The percent of VMT traveled by autonomous vehicle is a function market penetration, explored in the preceding section, and demand for travel as outlined in this section. The average ratio of VMT attributed to autonomous vehicles is 64% of all miles in the US by 2037. Estimates in this category are much higher in the market penetration rate of autonomous vehicles by proportion of the fleet because they account for the increased utility of shared or autonomous cars by up to ten times that of a standard vehicle (Arbib & Seba, 2017).

An interesting outcome of the travel demand literature is the second order effects of decreased or increased prices and traffic. Humans are highly price sensitive individuals and when prices drop demand will increase until the roads and traffic have reached capacity and the value of our time begins to outweigh the cost of commuting.
Parking: declining demand and increased efficiency

Fully autonomous cars will enable the endpoint of a trip to be bifurcated in two different locations for the passenger and the vehicle. In a single owner model, autonomous parking will allow the vehicle to be parked blocks or miles away. The owner only needs to un-park the car via their phone or key fob. This means that parking garages needn't be located in some central area, only within a time-distance catchment area that is convenient for each owner. In a shared ownership or TaaS model, the vehicle may remain in nearly continuous movement only pausing to pick up passengers or charge/refuel periodically. Premiums for convenient locations may erode when convenience becomes more elastic with time, distance, and scheduling.

Vehicle efficiency, behavioral changes, and spatial disaggregation are often cited as reasons for the projected reduction in parking demand through autonomous travel. Studies predict a possible reduction in parking demand of up to 90%. However, less than half of the studies surveyed included a timeline for their prediction. Of which, the average decline was 33% by 2035. Authors forecasting this metric are often architects, engineers, or designers as it is primarily a spatial issue.
It is estimated that autonomous parking narrows the width needed for a parking space by 20% to 25% just through spatial efficiency (Heaps, 2016). The average size SUV at 6.5' wide could fit into spots 7' wide or less (USA Today, 2007). Bertoncello and Wee (2015) estimate this reduces the need for parking area by 5.7 billion square meters in the US alone by the year 2035. That's an area size of West Virginia that can be reclaimed. If no human has to be in the car while it is parking, the doors don’t need to open, the mirrors can be folded, they can stack multiple cars deep, and placed inches from one another. However, the efficiency inside an area exclusively used for cars is offset slightly by the need to safely drop off and pick up passengers, which could be achieved with curbside spaces.

Figure 24: Forecast for Reduced Parking Demand from Autonomous Vehicles

<table>
<thead>
<tr>
<th>Source</th>
<th>Published</th>
<th>Parking Demand</th>
<th>Year</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kotte Arnowstreet</td>
<td>2016</td>
<td>17%</td>
<td>2035</td>
<td>Decline by 5.7 billion square meters by 2035 (based off of 900 million spaces at 400 sf per space)</td>
</tr>
<tr>
<td>Kotte Arnowstreet</td>
<td>2016</td>
<td>22%</td>
<td>2035</td>
<td>24 SF reduction in the amount of space needed in a stall.</td>
</tr>
<tr>
<td>Audi Living Futures</td>
<td>2016</td>
<td>20%</td>
<td>2020</td>
<td>Assembly flow first phase: Mixed Human and AV car scenario</td>
</tr>
<tr>
<td>Green Street Advisors</td>
<td>2017</td>
<td>50%</td>
<td>2017</td>
<td>Reduced ownership, AVs, and ride sharing could result in a reduction to parking requirements of 50% in 25 years</td>
</tr>
<tr>
<td>Audi Living Futures</td>
<td>2016</td>
<td>62%</td>
<td>2030</td>
<td>Audi Living Futures (Source: Car and Driver)</td>
</tr>
<tr>
<td>Walker Parking</td>
<td>2017</td>
<td>15%</td>
<td>2030</td>
<td>Based on Mary's graph, based on McKinsey curve</td>
</tr>
<tr>
<td>Henderson &amp; Spencer</td>
<td>2017</td>
<td>42%</td>
<td>2035</td>
<td>Citing McKinsey's reduction of 6.7 billion square meters by 2035, based on 800 million parking spaces</td>
</tr>
</tbody>
</table>

Figure 25: Increased Spatial Efficiency in Parking from Autonomous Vehicles

<table>
<thead>
<tr>
<th>Spatial Efficiency from</th>
<th>Published</th>
<th>Efficiency</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gensler</td>
<td>2017</td>
<td>60%</td>
<td>AV Standalone parking structure</td>
</tr>
<tr>
<td>Gensler</td>
<td>2018</td>
<td>55%</td>
<td>AV Below-Grade Parking</td>
</tr>
<tr>
<td>Gensler</td>
<td>2019</td>
<td>30%</td>
<td>AV Above-Grade Parking</td>
</tr>
<tr>
<td>Heinrichs</td>
<td>2018</td>
<td>60%</td>
<td>Using robotic parking</td>
</tr>
<tr>
<td>Fereira</td>
<td>2014</td>
<td>50%</td>
<td>A reduction of nearly 50% when compared to the area per car of the conventional parking lot</td>
</tr>
<tr>
<td>International Transport Forum</td>
<td>2015</td>
<td>80%</td>
<td>International Transport Forum 2015; but no date attached to projection</td>
</tr>
<tr>
<td>Zhang</td>
<td>2015</td>
<td>90%</td>
<td>In an urban SAV system, but no date attached to projection</td>
</tr>
<tr>
<td>Childress</td>
<td>2015</td>
<td>50%</td>
<td>Parking costs were cut in half to reflect better space utilization. No empirical evidence for this number</td>
</tr>
<tr>
<td>Boweck</td>
<td>2015</td>
<td>33%</td>
<td>Schlesinger (2014), parking costs for fleet operators are assumed to be 100% higher than for private drivers.</td>
</tr>
</tbody>
</table>
A Financial Forecast for Parking

8. Method

*Forecasting Cash Flows*

The future is always uncertain, but the meta-analysis of autonomous vehicle literature provides insight into the future of parking. Broadly speaking, car ownership and the cost of travel decreases, but trips and mileage increase. The demand for parking spaces declines, but the efficiency of properties is increased. With any emerging technology there are pushes and pulls that can paint an optimistic or pessimistic scenario. The focus of this work is not to determine the future of parking by arbitrarily aligning with one scenario or another. But by harnessing the power of probability that underlies uncertainty, we can better understand the spectrum of future possibilities.

In this work, I model implications of autonomous vehicles on parking garages by forecasting future cash flows. I apply a Monte Carlo technique to generate probabilistic outcomes of a discounted cash flow model using randomly generated scenarios. This approach allows us to establish our initial expectations of parking garages’ financial performance, model the currently expected economic cyclicality of the market, and apply volatility triggered by autonomous vehicles using four main variables. This method combines the strengths of traditional real estate valuation with market dynamics and informed volatility.

*Discounted Cash Flow Model*

Commercial real estate considers an asset’s value as the sum of its expected future cash flows, adjusted for the relative risk of actually realizing those revenues and the time it takes to receive them – the so-called discounted cash flow model. There are several fundamental inputs included in a DCF that are correlated with the cash flows that a commercial asset receives and pays out for its use. Namely, these include 1) revenue sources, 2) vacancy rate, 3) operating expenses, and 4) capital expenditures. The same inputs can be applied to a parking garage as an asset and serve as the mechanism in which I will simulate the impacts of autonomous vehicles. These inputs establish the expected cash flows of the asset less expenses to achieve the net operating income. It is at this income level that the assumption of an asset’s worth can be determined by summing these values and discounting them back at an increased rate the further they are in the future. This discounted total sum less any capital spent upon acquisition, will provide the net present value of a property. Net present value (NPV) as well as internal rate of return (IRR), which is the rate at which the property returns any capital initially spent to acquire it, are two important indications of the investment worthiness of a specific asset.

However, the integrity of the outcomes is limited in its accuracy by the inputs provided. Each input must carefully be selected to reflect the most realistic expectation of future realities without being able to ascertain them. Thus, the discounted cash flow model reflects a limited future by calculating the input variables given to a single outcome of cash flows. Geltner et al. (2012) document the problems associated with a deterministic discounted cash flow model, where one value is the end result. This is the fundamental fallacy of a deterministic future model that provides decision information today based on what the future should look like, not what the future will look like. The actual property outcomes almost always vary from the original assumptions. Thus, an additional level of sophistication can be added to a DCF to model the sensitivity of the property to certain variations of input variables like cost of capital, rent growth, or cap rate fluctuation. This sensitivity analysis helps understand the relative risk of a property in multiple deterministic future scenarios.
**Monte Carlo Simulation**

Monte Carlo Simulation is a mathematical technique that utilizes repeated random sampling to predict the probability of outcomes. It is an effective way to model the future when the outcomes are uncertain. It frees us from narrowing future outcomes to a few deterministic scenarios and instead quantifies the landscape of possibilities by their likelihood of occurring. These future possibilities are not drawn completely at random, but from a bounded set of expected parameters. To identify these parameters for an autonomous vehicle future, I referenced my meta-analysis that contains studies with simulations, scenarios, and forecasts and applied educated parameter bounds to my analysis. I believe that this realm of possible futures is helpful in outlining the relative risk associated with parking assets in an autonomous future.

This model is an extension of the forthcoming text from Geltner and de Neufville that uses Monte Carlo simulation as a tool for modeling uncertainty and flexibility in real estate (Geltner & de Neufville, 2018). To structure the financial forecast, I built three separate financial projections using the discounted cash flow model. The first is a deterministic 10-year discounted cash flow analysis of the parking garage without any autonomous vehicle impacts applied. The second is a 24-year discounted cash flow with impacts of autonomous vehicles applied to revenues, vacancy rate, operating and capital expenditures. The second scenario has no option to sell the asset before the end of the analysis period. The third scenario models the same anticipated changes in revenues and costs from autonomous vehicles, but with the ability to sell the asset in response to changes in financial performance at any point after the first year.

**Introducing Uncertainty**

In line with Geltner and de Neufville (2018), I first model the uncertainty in the rental and capital markets to mimic the cyclical, auto-regression, and mean reversion of real estate. This is achieved by applying historically-based parameters and factors to randomly generated values. I first establish a period length for the cycle, initial year, amplitude of the volatility, as well as variation of the volatility. Next, I apply an autoregressive parameter. We know that real estate as an industry does not experience extreme volatility like the stock market, but rather long, autoregressive cycles that are related to the trajectory of the period before (Brooks & Tsolacos, 2010). Lastly, I establish a mean reversion rate that influences the random outputs of the model back to the long term average market return and apply a correction in reversion rate to deal with convexity bias. We also know from longitudinal studies that real estate is mean reverting and tends to experience ups and downs that over time tend toward the long run average return, which has been documented to be at the level of inflation or below (Eichholtz, 1997). Through this simulation of market dynamics, these random values begin to mimic the real estate market as a whole and will serve as the backdrop for the next layer of uncertainty. Using these three types of market dynamics, the model creates a random 25-year forecast of variables that are then applied to property-specific variables.

The second introduction of uncertainty is not at the real estate market level, but at the property level. Just as a 25-year forecast was made for the market, I must generate a 25-year forecast specific to the parking garage influenced by what happens in the rest of real estate market. I establish a property-specific forecast by generating random numbers for the four variables I seek to test. Then I apply the parameters established from the meta analysis of parking demand by setting them as bounds to the random draw. Then I calculate the idiosyncratic risk, differential trend and correlation between the variables and tie them to the market as a whole. The result is a random 25-year forecast of the four parking-specific variables, anchored to the larger market that simulate the effect of autonomous vehicles and can then be input to the property pro forma.

**Combined Approach**

Market and property dynamics factors can now be applied to the two future scenario pro formas to simulate autonomous vehicle outcomes. The simulation objectively, randomly creates a new future forecast for the market and the property each time it is calculated. These
dynamics are filtered through each of the pro formas which are run with their respective periods: either a fixed 25 years or a random hold period, triggering a sale only when the property reaches a desired return or undesired loss. The Monte Carlo model generates a data table of 10,000 random trials representing range of resultant financial outcomes of the pro formas. Outcomes are then organized into probability distribution functions of standard property valuation metrics (eg: IRR and NPV) and compared to the base case pro forma, which remains unchanged. We can then examine various aspects of the distribution of possible outcomes (eg: mean, median, minimum, maximum, percentiles, and standard deviation). The characteristics of the probability distribution helps draw conclusions about how potential market conditions and future uncertainty affect the projected returns of the parking property.

9. Data

Below is a discussion of the primary pro forma inputs that were used to construct this model for a typical, structured parking garage with 250 spaces. The assumed investment for the asset was $20,000 per parking space which is slightly above the national average to construct a typical parking garage (Walker 2016). This yields an implied initial capitalization rate of 6.97%.

![Figure 26. Base Case pro forma Inputs used for Discounted Cash Flow](image)

**BASE CASE PROFORMA INPUTS**

<table>
<thead>
<tr>
<th>Number of Parking Space</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rental Revenue per Stall</td>
<td>$4,503</td>
</tr>
<tr>
<td>Rent Growth</td>
<td>0.5%</td>
</tr>
<tr>
<td>Vacancy Rate</td>
<td>38%</td>
</tr>
<tr>
<td>Vacancy Growth</td>
<td>0.5%</td>
</tr>
<tr>
<td>Opex Growth</td>
<td>2.4%</td>
</tr>
<tr>
<td>Opex Expense Ratio</td>
<td>30%</td>
</tr>
<tr>
<td>Capex Growth</td>
<td>2.40%</td>
</tr>
<tr>
<td>Capex Expense Ratio</td>
<td>1.00%</td>
</tr>
<tr>
<td>Selling Expense</td>
<td>2.00%</td>
</tr>
<tr>
<td>Discount Rate for PV</td>
<td>7.50%</td>
</tr>
<tr>
<td>Property Price</td>
<td>-$5,000,000</td>
</tr>
<tr>
<td>Salvage Value</td>
<td>$3,286,000</td>
</tr>
</tbody>
</table>

**Rental Revenue**

Rental income represents the fundamental value of real property. It is the most dynamic input into a financial model and best indicates the demand for a specific real estate commodity. Rental rates fluctuate around the market equilibrium price that maximizes the efficiency of occupied and vacant space which can be understood as the demand for that project. Basic parking garage rental fees can be expressed as two types of income: hourly and leased. Monthly or even yearly leases offer a more stable and predictable cash flow, but are usually offered at a discount and cannot immediately respond to changes in demand. Hourly parking rates can be dynamically priced based on the time of day or year, but can be unpredictable and thus demand a higher starting price that may be slightly discounted up to a certain time limit. Hourly rates are charged in half hour or hour increments and can allow for some excess cash flow as payments overlap. Or in a monthly rate setting some garages, presuming a certain amount of vacancy in their hourly stalls may choose to oversell the number of monthly parking passes to the number of stalls by a factor of 10-20% (Anglyn, 2013). The ratio between hourly and monthly subscriptions can shift within the same property because parking spaces are a nearly homogeneous commodity within the same property.
For this study, I examine both monthly and hourly rates as well as gross revenue per stall that blends the two. The rental rate data is derived from a variety of different sources but for this study is focused on garages in metropolitan areas in the US. Colliers (2012) surveyed private parking operators in CBD's of 19 different major metropolitan areas and found an average monthly parking rate of $6 per hour or $166 per month. This is similar to a survey of 56 different metropolitan areas that found a median monthly rate of $120 and an average of $157 using data from ParkMe, an app and web-based parking service (Cortright, 2016). Cortright draws a sample of five parking lots and garages closest to city hall in the largest city in fifty metro areas and averages their rates. They then aggregate the city averages to establish the national average rate.

In my own data collection from the same source, I established a national average based on individual properties from each of the same metro areas. My analysis showed an average hourly rate of $12.55, average daily rate of $31.34, and average monthly rate for reserved and unreserved spaces of $366.62. However, these rates include both parking lots and garages. Further narrowing my selection, I found that the average rates exclusively for garages charged a small premium, between 2.4% and 8.5%, of $13.36 per hour, $34.01 per day, and $375.26 per month. It is important to note that these figures represent potential gross income, similar to asking rents in other categories of real estate.

Figure 27. Hourly, Monthly, and Vacancy Averages for Garages, data from ParkMe

<table>
<thead>
<tr>
<th></th>
<th>Garages</th>
<th>Garages and Lots</th>
<th>Premium for Garages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hourly Average</td>
<td>$13.36</td>
<td>$12.55</td>
<td>6.5%</td>
</tr>
<tr>
<td>Daily Average</td>
<td>$34.01</td>
<td>$31.34</td>
<td>8.5%</td>
</tr>
<tr>
<td>Monthly Unreserved</td>
<td>$293.47</td>
<td>$288.27</td>
<td>1.8%</td>
</tr>
<tr>
<td>Monthly Reserved</td>
<td>$457.05</td>
<td>$444.97</td>
<td>2.7%</td>
</tr>
<tr>
<td>Monthly Average</td>
<td>$375.26</td>
<td>$366.62</td>
<td>2.4%</td>
</tr>
<tr>
<td>Occupancy Average</td>
<td>64.1%</td>
<td>62.4%</td>
<td>2.8%</td>
</tr>
<tr>
<td>Average Spaces</td>
<td>246</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

I have elected to calculate rental income based on average revenue per stall, given the unknown ratio between hourly and monthly stalls and the great degree of separation their annualized rates. Revenue per stall is a more effective way to measure asset performance as it equalizes differential revenue factors of hourly versus monthly, overselling, daily rate discounts, or free parking periods. However, there are some challenges using this figure.

The industry typically reports revenue per stall on a net basis including vacancy which aggregates income across an entire year. This makes it difficult to ascertain the actual capacity of the asset and accurately model its performance. There is even a great degree of separation in reported revenue per stall when examining both industry reports, audited financial statements, and self-reported data. VTP! (Litman, 2017) is among the most conservative figures stating net revenues between $1,800 for urban parking structures and $2,400 for underground structures. Park24 (2016) reports $2022 net revenue per stall in their 2016 annual report, but with a high degree of vacancy (54%). International Parking Institute cites average net revenue per space for commercial operators as $2,458, but can range up to $3,500. Indigo, which owns a substantial portfolio in the US, reports a net revenue average of $3,713.25 across their international holdings.

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Information available at https://www.parkme.com/
For the purpose of this study, I have taken a conservative approach to forecasting gross revenue per stall by taking the average monthly asking rent for a parking space from the data collected (ParkMe, 2017). It relates closely with both the gross and net figures quoted throughout the industry when considered before and after vacancy.

Rental revenue is also modeled with an escalation or growth rate. Good practice for modeling rental growth rates is to mimic inflation in mature markets according to a long range real estate study by Piet Eichholtz (1997). Thus, the upper bound for rental growth would be 2.4% (Knoema, 2017). On the more conservative side is an industry report by IBIS which predicts sluggish growth from 2016 to 2021 of .05% per year (IBIS, 2016).

**Rental Revenue and Autonomous Vehicles**

Because rental rates are among the most dynamic of parking property variables, they will be the first to respond to fluctuations in demand as a result of autonomous vehicles. Parking demand can be extrapolated through a series of positive and negative impacts on demand that factor in demographic, economic, and technological shifts. These shifts will ultimately yield the number of vehicles in the US and how often and how long they will need to park. The first factor of demand is the overall number of vehicles in the US which is predicted to decrease on the consumer side by 43% (Schoettle & Sivak, 2015) to 82% (Arbib & Seba, 2017). This is a combination of getting more mileage out of electric vehicle life cycle, increase in ride-sharing, and a decrease of individual car ownership in favor of other transportation services. However, the predicted proliferation of TaaS (Transportation as a Service) and autonomous fleet and commercial vehicles will increase as a percent of remaining vehicles.

The overall mileage driven is expected to increase in nearly every scenario of autonomous vehicles. This is a factor of more productive time while traveling, a reduction in travel costs, and return trips without passengers aboard. The percent of VMT performed by autonomous, electric vehicles is predicted to be between 25% (Boston Consulting Group, 2017) to 95% (Arbib & Seba, 2017) by 2030. The average speed of travel in an autonomous vehicle will increase over today’s vehicles from an average of 27.9 mph to over 30 mph up to 45 mph (Childress et al., 2015). Each new model of electric vehicle has a greater battery life and range. The Tesla 3 and Chevy Bolt, have electric ranges around 250 miles, with a charging time of 60 to 180 miles per charging hour. This means that driverless cars will travel farther, faster, and more efficiently all decreasing the need for parking - or parking in very urban locations.

Nearly all autonomous vehicles currently on the market and promised in the future are hybrid or all electric. This means that there will be a growing demand for electric vehicle charging stations as autonomous vehicles hit the road. Parking garages can easily fulfill this need if properly planned and wired and the hourly rental rate could be increased to reflect this service. Other opportunities for rental income stem from the fleet demand. TaaS fleets of autonomous vehicles will see many more riders and miles a day which indicate a need for more frequent cleaning and maintenance. Instead of offering a valet service, parking garages can easily accommodate a detailing and service station in the footprint of just a few parking spaces.

Individual car ownership is predicted to decline which could mean a decline in monthly or yearly parking space leases as individual owners transition to a different mode of ownership or transportation. Most scenarios predict a substantial increase in demand for fleet-based TaaS trips (Kockelman, 2015; Arbib & Seba, 2017). This could mean that master leases for fleets of autonomous vehicles could increase in volume as well as the probability of renewal.

Potential increases in the demand for parking will arise as cities regulate parking and autonomous vehicles differently. Cities are permitting fewer and fewer parking stalls to be built, with some cities classifying entire zoning districts with zero required parking spaces.
Existing parking structures in prime locations with good connectivity in roads, utilities, and telecommunications could see an increase in demand. Furthermore, the advent of autonomous vehicles will decouple parking location from destination allowing redevelopment of surface lots into other real estate uses. This will drive demand toward purpose-built garages for autonomous, electric vehicles.

**Vacancy**

Vacancy in commercial real estate represents the relative demand for a product as well as the natural vacancy that occurs when turning over space to new occupiers. These can be applied to both hourly and leased parking spaces with an added layer of complexity: turnover. Commercial real estate occupancy last for years, whereas parking space occupancy lasts only a matter of minutes. This means that the turnover for a single parking space can be quite high and the aggregate utilization can remain low.

Pierce and Shoup (2015) cite the ideal vacancy for maximizing profit of a parking garage as 50% and maximum practical system efficiency is 15-5%. These figures are difficult to reach and even harder to maintain as demand fluctuates significantly throughout the day and week. For instance, the average vacancy cited in a downtown survey of Los Angeles public parking garages was up to 90% on weeknights and 62% on weekends (Kimley Horn and Associates, 2003). Municipal parking garages are almost exclusively charged on an hourly basis, but private parking garages have both hourly and monthly users. Unfortunately, there has not been substantial research that definitively separates out the vacancy of commercial parking structures by monthly or hourly users so like revenue per stall, it will remain an aggregate, blended rate for the entire parking asset. For this model, I will apply a blended vacancy rate that aggregates weekly and seasonal fluctuations for both hourly and monthly users. This will yield the probability of occupancy in a space at any given time. Based on data obtained from ParkMe, the average aggregate vacancy for a parking garage across 50 major metropolitan areas in the US is 38% during the week surveyed.

Most forecasts and simulations point to an increase in parking vacancy based on fewer cars on the road, increased utilization rate of vehicles, and increased efficiency of space in parking spaces. The reduction of the number of vehicles in the US is predicted between 43% (Sivak & Schoettle, 2015) and 82% (Arbib & Seba, 2017). Autonomous vehicles can serve more users, more functions, and remain in motion for a greater part of the day than traditional cars. The utility of autonomous vehicles increases especially in forecasts with a network of fleet-operated vehicles. The average utilization rate for autonomous vehicles is projected to be 40% (Arbib and Seba, 2017) as opposed to the utilization rate of a traditional car that is used 4-6% of the time (Shoup, 2011) making the vacancy rate in an autonomous setting ten times higher than the current average. Based on the meta analysis for the decrease in needed parking spaces by 2033 there will be a need for 41% fewer parking spaces. Despite these pressures that increase vacancy rates, the parking garage has some advantages over street and surface spaces that must be accounted for. Garage spaces can easily accommodate electric charging stations, car detailing service, and other services that will be important with shared, electric, autonomous vehicles. Additionally, vacancy my decrease as curbside spaces are repurposed for other public uses, and parking lots are easily redeveloped into other real estate uses.

**Operational Expenses**

Operational expenses are the necessary ongoing costs of owning and managing a real asset. Common expenses that fall under this component are salaries, maintenance, utilities, insurance, property tax, leasing commissions, payment systems, accounting, legal, and management fees. Parking garages alone have relatively low operating costs as they require a relatively small labor force, little maintenance, and predictable utility usage. While other real estate uses are measured in dollars per square foot per month, parking garage expenses can be measured in cents per square foot per month. Operational expenditures for garages average about $0.19 (Litman, 2015) to $2.27 (Mobley, 2015) per gross building square foot per month (Litman, 2015) to whereas other real estate uses range from $1.40 to $2.67 on the national level (Mobley, 2015).
The average operational cost of parking garages in 2006 was estimated at $500 per stall per year (Bier et al., 2006). Similar numbers were recorded in 2012, ranging between $600 to $800 for parking structures in urban locations (Litman, 2015). Reported operational expenses in 2016 were roughly $700 for SP Plus and $800 for MVP REIT (SP Plus, 2017; MVP REIT, 2016). Expenses represent about one third of the potential income of the parking spaces. Some of these expenses scale based on occupancy, like payment systems, utilities, or cleaning. However, a portion of these expenses that are fixed to matter the daily occupancy, like taxes and insurance. There is a broad spectrum of operational approaches to parking garages that can impact demand based on convenience. For this study, I have set the expense ratio parameter between 25% to 30% of gross rental revenue that will be adjusted each year by an expense growth rate.

In the autonomous future, cars will not be the only part of our lives that becomes automated. The cost to automate other parking technologies like surveillance and payment will likely drop with increased connectivity and decreased cost of data. Autonomous vehicles will already come with the ability to pay for parking without cause for a human operator or ticket system, allowing for personnel costs to be eliminated. Payment platforms will be electronic and require little to no maintenance. However, telecommunications and utility costs will increase with electric, driverless vehicles. For these reasons the operational expense growth rate upper parameter has been set at the long term inflation forecast for the US at a rate of 2.4% (Knoema, 2017). The lower parameter has been set to 0% as the cost of digitization, automation, and less expensive utilities will likely reduce the operating costs of a garage.

**Capital Expenditures**

Capital expenditures are expense allocations intended that maintain a property's operational value. Typically, these funds are budgeted as part of a monthly transfer/allocation to a reserve account so that the property has access to funds for future projects or emergencies. Over the lifetime of the property these funds can be drawn upon to repair, replace, or improve aspects about the asset. These actual cash outlays are the verbatim meaning of the capital expenditures, but the industry term often encompasses both the amount set aside and the amount spent. Capital expenditures only become fully tax-deductible when they are spent on the actual building. However, I am limiting this analysis before tax is calculated, so I have annualized the capital expenditures and treated it as part of actual property expenses included before NOI is calculated.

The average capital expenditure by NCREIF in its annual index equates to 1.9% of market value or about 30% of NOI (NCREIF, 2016). This goes for all commercial real estate classes and is not specifically broken out for parking garages. Capital expenditures for parking garages are low compared to other real estate uses. The useful life of the equipment and structure is relatively high with low maintenance and failure rate. This is what makes parking an attractive investment. The capital expenditure for this analysis is projected at 0.9%.

In the future, the capital expenditures for parking garages could be very high for them to remain relevant. These improvements include charging stations, occupancy detection, iOT connection, and other car-related services. Although electric vehicles only represent 0.8% (Shahan, 2017) of the US fleet, that percentage is expected to grow significantly. Parking garages may need significant physical upgrades to charge these vehicles including increased capacity of electrical panels, new electrical conduit, charging payment stations, and may even renewable energy systems. Real time space availability of will be critical in order for autonomous vehicles to locate vacant spaces which require sensors, cameras, WiFi, and data storage costs to connect the structure to the network of vehicles. New vehicle-related service opportunities may evolve such as fleet detailing services, battery swaps, conversion and customization shops, or maintenance locations will require both an infusion of capital and allocation of space. For these reasons, the escalation for capital improvements have been set at a minimum of 1% and an upper limit of 10%.
**Capitalization Rate**

Capitalization rates are one of three prevalent ways of establishing asset value for commercial real estate in the US. Capitalization rates are established over a period of time using like-kind transaction data for the same or similar markets by dividing the cash flows by the value the property transacted. Those market-determined cap rates can then be applied to new properties to back solve for the value that can be expected at market. This data gives a sense of how the market perceives this real estate product. The relative amount of risk can be extrapolated from the relationship of asset value to cash flows, the greater the spread between the two, the larger the cap rate and the riskier the asset is perceived to be. Over time, the expectation is that the cap rate when acquiring the property will be higher than when selling the property. This compression indicates appreciation of value over the course of the asset tenure. The cap rate upon selling a property is a good barometer for what the required return is for a property inclusive of all capital costs. For this model, I will treat the going out cap rate as the market rate for the weighted average cost of capital which allows us to calculate the discount rate for the present value of the property as well as the terminal value of the property.

Parking garages are frequently traded as part of building transactions and thus the availability of data on this asset is difficult to extrapolate. I have analyzed data from public parking companies’ financial reports (e.g.: MVP REIT, SP Plus, Infra Park, ABM), real estate advisory firm publication (RERA), and real estate transactional databases (Real Capital Analytics) and appraisals to determine the upper and lower bounds for parking garage cap rates. Real Capital Analytics (RCA) reports cap rates on transactions at an average of 6% over since 2015 (Real Capital Analytics, 2017). Other sources quote average cap rates nationwide of 6.3% to 7%, but can range from 4.5% to 10% (Anglyn, 2015). For this analysis I have set the mean reverting cap rate to 7.5% with a range from 4.5% to 10%.

In an autonomous future the expected change in demand is modeled by modulating rents and vacancies. By modulating cap rates, specifically upon property exit, we can model the worth of a property. And by modeling the worth of the property, we can model the investor or owners’ appetite and value of the relative risks and rewards associated with a parking garage. I predict that we will not see a decrease in cap rates over the short term as demand for parking stalls weaken and properties are demolished or repurposed. In the long term, parking garages may find new utility in the autonomous age and experience increased demand through scarcity assuming few supply limited by the effect of future low or no minimum parking requirements.

**Hold Period**

The typical analysis period for a real estate asset is 10 years. This period may be rooted in tax implications of depreciation in the 60s and 70s rather than modern regulation and investor behavior (Fisher & Young, 2000). Holding periods vary greatly depending on the investor, quality of asset, market timing, and tax regime. Gau and Wang (1994) cite an average of 8 years while Fisher and Young (2000) find that investors hold for 11 years. More recent long range studies of investment quality real estate suggest that IRR is maximized at 7 years (Feng & Geltner, 2011). Parking garages are assumed to follow the trends of other real estate classes and are frequently bought and sold as part of a building transaction.

This analysis simulated both fixed and flexible investment holding periods. The fixed hold periods are 10 to simulate the normal analysis period for real estate and 25 years to allow for the full force and effect of autonomous vehicle impacts to be realized. The flexible hold period scenario in this analysis allows for a sale at the end of any year in the analysis period after year two, with a forced sale in year 25.
10. Results

The results of the Monte Carlo simulation will be examined first by looking at the three main indicators of financial performance and second by each pro forma's performance in the simulation. This allows for a comparison of relative performance in each metric as well as a dissection of each pro forma scenario.

Results by Financial Indicator

The first financial indicator is the net present value (NPV) of the asset at time zero. The NPV is the result of discounting the sum of future cash flows by a specific discount intended less the initial investment made. The next is the internal rate of return (IRR) which is the rate at which all future cash flows equal zero. It can be understood to mean the rate at which an investment earns, or does not earn, back its original value. Internal rate of return is a good barometer to know if a property is indeed generating income, but it is not a good indicator of quantifying the profitability of a property. Although either metric alone does not provide an accurate idea of investment worthiness, together these metrics can give us a general idea profitability. Finally, investment holding periods greatly influence its financial performance depending on timing of the investment relative to the market cycle and is one of the primary observations of this model. These financial indicators will be examined by their probability of performance as well as mean, minimum, and maximum values over the range of simulations.

Net Present Value

In each of the three pro formas the mean Net Present Value was negative. This is not to say that the property is not generating revenue, or even profit. In most years, even in the inflexible 24-year hold period, are profit positive. However, the further the cash flows are in the future, the more heavily they are discounted back to present tense. The original base case pro forma is the only scenario that maintains a positive cash flow over the entire fixed 10-year period. The other scenarios experience some years of negative cash flow that vary at random. The average annual cash flow of the flexible case is $182,382 million versus the inflexible at $239,293 million and the base case at $357,434.

Despite consistently positive cash flows, the base case pro forma's NPV at the end of the period is -$236,909 because of the cap rate increase from an implied 7.0% to 7.5% and a sluggish rental growth rate. Over a series of 10 simulations running 10,000 possible outcomes in each calculation, the inflexible pro forma exhibited a negative mean NPV of -$1.9 million with the 5th percentile range of -$3.0 million and -$966,863. The flexible pro forma over the same simulations had a mean NPV of -$1.0 million and a range of positive $1.2 to -$2.0 million.

These distributions (across 10,000 simulation outcomes) are displayed in graphically as a cumulative and frequency probability distributions in Figures 11 and 12. The cumulative distribution indicates that the flexible case has a higher probability of achieving a higher NPV than the inflexible case by its position to the right. Indeed, the inflexible case has 99% certainty of achieving a negative NPV and the inflexible case as an 80% probability.

However, it is important to note that the flexible scenario has a smaller downside probability and a higher upside probability. This is because of the ability for the flexible scenario to trigger a sale based on a 20% threshold of either gain or loss. The frequency distribution graph shows that the inflexible pro forma has a more evenly distributed probability as it has a fixed holding period that is fully exposed to the ups and downs of the market over a considerable period of time.
A simpler way to visualize the flexible and inflexible cases is to plot the difference between their NPV outcomes. In the Figure 28 below, we can observe that the vast majority of outcomes (%) the flexible case outperforms the flexible case, often by millions of dollars. This is not to say that the flexible case has significantly positive cash flows, only that their relative value when compared with that of the inflexible case is significant.

Figure 28. PV Cumulative Distributions

![PV Cumulative Distributions](image)

Figure 29. NPV Frequency Distributions

![NPV Frequency Distributions](image)

Figure 30: Difference Between Flexible Minus In Flexible (As Function of Inflexible NPV)

![Difference Between Flexible Minus Inflexible NPV](image)
**Internal Rate of return**

The rate of return changes each year with fluctuations in net available cash flow. As such, the IRR measure creates much more variety than the NPV calculations. In this measure of property performance we see quite the inverse dynamic that we saw with NPV. The mean IRR was 2.9% for the inflexible case with a range from -0.58% to positive 5.5%. The mean IRR for the flexible case was 1.58% with a range of -13.1% to positive 16.4%. The inflexible scenario outperformed the flexible scenario 64% of the time. This is largely a function of the much shorter average holding period of the flexible scenario that has a lower IRR by way of having fewer years during which it can earn back the original investment.

In the cumulative distribution shows that in 5% of 10,000 outcomes, the Flexible IRR was below the minimum IRR of the inflexible case. Because the cumulative function is built by dividing the entire range of outcomes into twenty percentiles, we see small aberrations at the 5th and 95th percentiles in the cumulative function where the range of the flexible IRR extends beyond the bounds of the flexible range. For example, the inflexible pro forma never reaches an IRR of below -7.1%, thus we see the aberration in the flexible IRR probability.

In the frequency distributions below we see that the flexible case does not account for any IRR results below 20% because of the stop-loss trigger for selling the property. Yet because of that trigger, the flexible case as a lower IRR on the down side because of the scenarios ability to sell the asset thus reducing the cash flows received over time and thus the IRR. However, the right-leaning tilt of the flexible IRR indicates that it also has a higher probability of a positive IRR on the upside. Contrast this with the left-leaning distribution of the inflexible case indicating a higher probability surround a 0% IRR with a steep decline thereafter.

**Figure 31. IRR Cumulative Distributions**

![IRR Cumulative Distributions](image-url)
Hold Period

There are three investment periods modeled by this simulation that are distinct to each pro forma. The base case pro forma follows the traditional 10-year real estate horizon. A longer time horizon was used in the subsequent pro formas in order to more fully display the impact of autonomous vehicles. The flexible case pro forma has the ability to trigger a sale based on the performance of the asset reaching a certain level of gain or loss. The average hold period (see Figure 33) for the flexible pro forma was 6.7 years over the course of 10 simulations representing 100,000 possible outcomes. Periods could vary between 2 and 24 years as no sale was assumed in the first year of analysis. It is interesting to note that the most frequent holding period was 2 years with 23% of simulations triggering a sale as soon as it was possible to do so. Less than two percent of simulations held the asset for the full 25-year period.

Results by Pro Forma Scenario

The period of this financial analysis extends to 2042, when the average of the literature surveyed herein predict 55% of all vehicles on the road will be autonomous driving over 63% of miles traveled in the US at a cost of $0.27 per mile. By that time, parking demand will have decreased, or its spatial efficiency increased, by 33%. In the majority of simulations, the NPV remained negative and the IRR was well below market. Here I will discuss the exposures of parking cash flows in the short and long term as a result of autonomous vehicle predictions.
**Base Case Pro Forma**

The base case pro forma was modeled after realistic expectations for future profitability of a generic parking asset modeled after the national average. The value of the property based on its year 1 cash flow is not far from market reality today. Current trades on parking have an average reported cap rate of 6.4% (Real Capital Analytics, 2017). If cap rates remain below 6.6% in the initial pro forma, the NPV would be positive. However, interest and cap rates are predicted to rise in the near term as the growth cycle peaks. Parking may still remain an attractive investment, but with prices nearing their peak, and autonomous vehicles in the present, investments should be scrutinized for location and possible alternate uses.

**Inflexible Pro Forma**

The inflexible pro forma has the most profoundly negative NPV, yet a positive IRR that falls between the other two scenarios. This is simply a function of the extended hold period and an average yearly cash flows of positive $239,293 million. The lengthy timeline for this simulation may span two or more real estate cycles, that normally span 16 to 20 years, yielding increased variation in cap rate cycles as the sale is fixed in year 25. At that time, the resale value of the parking garage could have been negative in some cases based off of an exclusive cap rate valuation approach. This model accounted for a residual value of the parking garage of 67% of the original purchase price. This is assumed to be the land basis in the price and represents the salvage value of the property. To the extent that this analysis can simulate, a 24-year investment without redevelopment, repositioning, or resale does not represent significant value.

**Flexible Pro Forma**

The flexible pro forma presents the best case for the relative risks and rewards for parking garages. The average hold period was three years less than the original pro forma. This suggests that at a point in the near future, parking will experience enough of a shift in demand that a decision becomes critical: to hold or sell. The NPV of early sales were among the most significant, whereas with a shorter investment period the IRR outcomes were negligible. However, positive NPV outcomes stretched in some cases until year 12, before beginning to lose value. Overall, the likelihood of a positive NPV is only 20%.

11. **Discussion and Conclusion**

The results of my research and analysis suggests that parking in the short term is a risky investment and in the longer term may not be a viable asset. There is a high degree of exposure of parking garages to changes created by autonomous vehicles illustrated by significantly negative net present day values and minimal returns. This exposure will continue to grow as the stock of parking spaces increases with minimum parking requirements for new construction.

This model provides insight to a land use and space market that is largely not considered for investment purposes. This largely overlooked asset class will become a proving ground for the impact for driverless technology. This analysis provides a unique perspective of property-level dynamics in a randomly simulated autonomous vehicle forecast. It has introduced a new level of analysis to the Monte Carlo simulation tool developed by Geltner and DeNeufville (2018) by introducing variability in outputs related to autonomous vehicles, but also variability of inputs for a more robust exploration of this asset class.

Given the limited availability of parking data, my ability to model property-level details such as utilities, payment systems, and ratio of hourly to monthly spaces was limited. The information used emulates an average parking structure using national average and no location
specific subtleties. However, using aggregate data allowed me to focus on globally applicable inputs without becoming overly prescriptive about idiosyncratic details.

Other limitations include the identification strategy for translating the existing literature on autonomous vehicle into the variables that can be input in a parking pro forma. More detailed information about specific market demand factors for parking would have strengthened the relationship between autonomous vehicle inputs and parking demand outputs. However, because we have never experienced a world with ubiquitous autonomous vehicles before, even information that directly links legacy automobile facts to parking may not be the same going forward, especially considering the current and predicted shifts in the landscape of car ownership.

Finally, this research does propose a solution or approach in response to the bleak outlook for parking. Another simulation aspect that could be incorporated is a mechanism by which the parking garage could be modeled as an alternative land use. Using the stop-loss trigger, the simulation could draw upon realistic construction costs for other uses that could plausibly be introduced into a retrofitted parking garage. At a certain point, parking revenues may become inconsequential enough that recapitalization, renovation, or demolition and replacement of the garage is financially feasible. Last mile logistics space, apartment amenity floors, autonomous self-storage facility, data centers, or even indoor food farm may one day replace defunct parking decks.

Yet, there is something that can be done that will protect the viability of these assets, repurpose urban land human-centric uses, and make the most of valuable resources. With up to 2 billion parking spaces in the US, there is arguably an oversupply of parking in aggregate. By better managing the parking supply we currently have in tandem with other transportation options we could remove the need to build additional parking. The first step in containing the parking space market is to establish maximum parking requirements in place of maximums. Or, in certain areas well served by other mobility options, it may be possible to eliminate parking requirements all together. By requiring parking we squander expensive urban land, make other beneficial land uses more expensive, and spend resources on a building that will become outmoded at large. Some cities like Santa Monica and Salt Lake City have already opted for this new approach to planning and development.

In other locations, new parking development may still be required before autonomous vehicles attain significant market share. At minimum, these parking investments should be made with the future in mind. Designers such as Gensler, Arrowstreet, SWA, and Walker Parking have already begun to explore, estimate, even build for autonomous vehicles (Arrowstreet, 2017; Gensler, 2017; SWA, 2017; Smith, 2017). Although there is no such thing as "future-proofing": small improvements in the beginning may help to extend the life of the parking garage and offer some valuable flexibility in an uncertain future.

Figure 34 and 35: Arrowstreet phased design for autonomous parking garage
By 2020 the next automobile revolution will begin and it will be the second time that cars have dramatically changed the shape of our cities, hopefully this time for the better. By building cars without drivers, means being able to build cities without new parking. And cities without excessive parking will look unlike anything we've known for the last 100 years. With more than 323 million people living in cities in the US and 41 million to be added by 2030 (Census, 2016), the obsoletion of space devoted to parking will continue to be a concern in cost, efficiency, and availability. If we seize the opportunity today to limit new construction of a soon to be outmoded model, we can make our cities cleaner, quieter, and more equitable.
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