The Impact of Autonomous Vehicles on the Real Estate Housing Market in the United States

by

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Submitted to the Department of Architecture and the Center for Real Estate on January 13, 2023 in Partial Fulfillment of the Requirements for the Degree of Master of Science in Real Estate Development

ABSTRACT

The mode of transportation has a significant impact on the design and layout of cities, and the advent of autonomous vehicles (AVs) is expected to bring another shift in transportation that will likely impact the way cities are designed. The initial adoption of AVs is likely to occur in the form of shared autonomous vehicles (SAVs) or driverless ride-hailing services. This thesis analyzes the impact of AVs on the housing market, examining it at both macro and micro levels. The macro level analysis examines the complementary impact of SAVs on public transportation systems and identifies the metropolitan areas that are most likely to experience significant changes as a result of the deployment of SAVs. The micro level analysis examines the demand side of specific housing price change in San Francisco, utilizing a historical rent gradient model, by considering changes in commute cost and time. Additionally, the supply side of the analysis explores the potential conversion of parking spaces into housing.

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I. Introduction

The mode of transportation has a significant impact on the design and layout of cities. For example, narrow streets in Rome were originally designed for pedestrians, while the winding streets in New York were created to accommodate horse-drawn carriages. The advent of automobiles led to the development of straight roads with no constraints on movement. With the arrival of autonomous vehicles (AVs), we are seeing another shift in transportation that will likely impact the way cities are designed.

AVs are expected to significantly impact the way people move, providing more efficient and convenient travel options. AVs may increase mobility for those who cannot drive and make long-distance travel more comfortable. They may also reduce the number of cars on the road through the use of shared AVs.

It is essential to consider how the deployment of AVs may impact real estate values, especially as the rate of deployment progresses, even if full deployment is still several decades in the future. The initial adoption of AVs is likely to occur in the form of shared autonomous vehicles (SAVs) or driverless ride-hailing services such as Uber and Lyft. While it is challenging to predict the exact impact on real estate values in the distant future, it is useful to make predictions for the near future with partial deployment of AVs.

While the adoption of AVs may affect different types of real estate in different ways, it is expected to have a significant impact on the housing market. The focus of the paper is on the impact of AVs on the housing market at the macro level, with a detailed analysis at the micro level considering both demand and supply factors. The macro level analysis will examine the complementary impact of AVs on public transportation systems. The analysis will identify the key factors that influence this impact and gather relevant data for various metropolitan areas. The data will be analyzed to determine which metropolitan areas are most likely to experience significant changes as a result of the deployment of AVs. Once the metropolitan area that is anticipated to experience the greatest impact from the macro level analysis has been identified, a micro level analysis for that specific metro will be conducted. On the demand side, the adoption of AVs may affect people's decisions on where to live by making commuting to work easier. This could potentially change the demand for housing in certain locations. On the supply side, the reduced demand for parking spaces due to AVs could lead to the conversion of parking spaces into other uses, such as housing. This could potentially increase the supply of housing in certain areas.

II. Macro Level Analysis

1. Impact on Public Transit

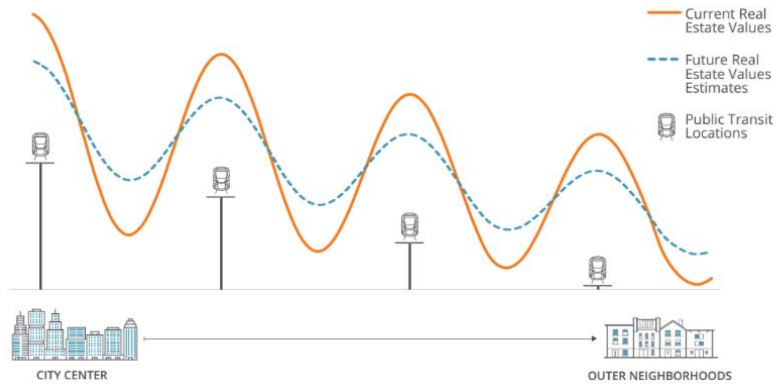
There is ongoing discussion about the role of autonomous vehicles (AVs) in relation to public transit, and how this could potentially impact housing prices based on location. Some people believe AVs will completely substitute public transit, while others think they will complement it. This debate has significant implications for how housing prices may be affected by proximity to transportation options, and I present both below.

1.1. Substitution Effect

Blake (2019) discovered that as gasoline prices increase, the premium on housing in areas with high rates of commuters driving alone (a proxy for access to alternative modes of transportation) also increases. In other words, when gasoline prices increase, homes in areas with access to alternative modes of public transportation become more valuable. On the other hand, as the cost of commuting decreases, the premium on housing in areas with access to alternative modes of public transportation also decreases.

Brookfield Public Securities Group (2020) predicted that real estate premiums related to proximity to public transportation will decline or disappear as commuting and leisure travel become more affordable and convenient, potentially narrowing the gap in real estate values based on proximity to public transit.

Figure 1: Real estate values relative to city center and transportation



Source: Brookfield Investment Management

The potential impact of AVs on the transportation industry can be inferred from the disruption caused by companies like Uber and Lyft in traditional modes of transportation. Uber and Lyft are companies that offer ride-hailing services, and it is likely that AVs could be used in similar ways in the ride-hailing industry.

Clewlow et al. (2017) conducted a survey in seven major metropolitan areas to examine the adoption, use, and initial effects on travel habits of ride-hailing services. They discovered that shared mobility options in major cities in the United States may discourage people from using bus services and light rail (a 6% and 3% decrease in usage, respectively), but may serve as an additional transportation option for commuter rail (a 3% increase in usage). This data demonstrates that the substitutive versus complementary nature of ride-hailing varies considerably based on the prevalence and quality of public transit services, but the net effect is negative. Some people may choose to use ride-hailing services instead of public transit because they believe the transit options are slow, do not have convenient stops, are not available at the times they need to travel, or are unreliable.

1.2. Complementary Effect

A study by Hall et al. (2018) found that Uber functions as a complement to public transit rather than a substitute, particularly for small transit agencies that had lower levels of initial ridership before Uber was established and agencies in large cities. It is mainly because customers use Uber to avoid the limitations of fixed routes and schedules, and because transit users in large cities tend to have a wider range of incomes, allowing for complementary effects to arise from the group of riders who can afford to use Uber. One possible explanation for why Uber serves as a supplement rather than a replacement for transit may be that transit remains significantly cheaper to use. In Hall et al. (2018) case study, transit is inexpensive enough that the convenience provided by Uber in complementing the transit system is more significant than its potential to replace using transit.

Shared autonomous vehicles (SAVs) have the potential to encourage higher usage of public transportation systems, reduce traffic congestion, and decrease the distance traveled by private vehicles, according to a study by Lau & Susilawati (2021). When SAVs were introduced to a transportation network using headway-based assignment in Kuala Lumpur, passenger trips on local public transit options such as Light Rail Transit (LRT) and Mass Rapid Transit (MRT) increased by 3.2% overall, and the distance traveled by private vehicles decreased by 6%. The introduction of SAVs also led to an improvement in first and last-mile connectivity by filling gaps in existing public transit networks and providing shared mobility services to underserved areas. However, the study found that this effect was only observed when the cost of using SAVs decreased by up to 15%. When the cost decreased by 20%, there was a significant increase in the number of passenger trips taken with SAVs and a decrease in the number of trips taken with public transit. This suggests that when the cost of using SAVs becomes too low, people may be more likely to use them for their entire trip rather than combining them with local public transportation.

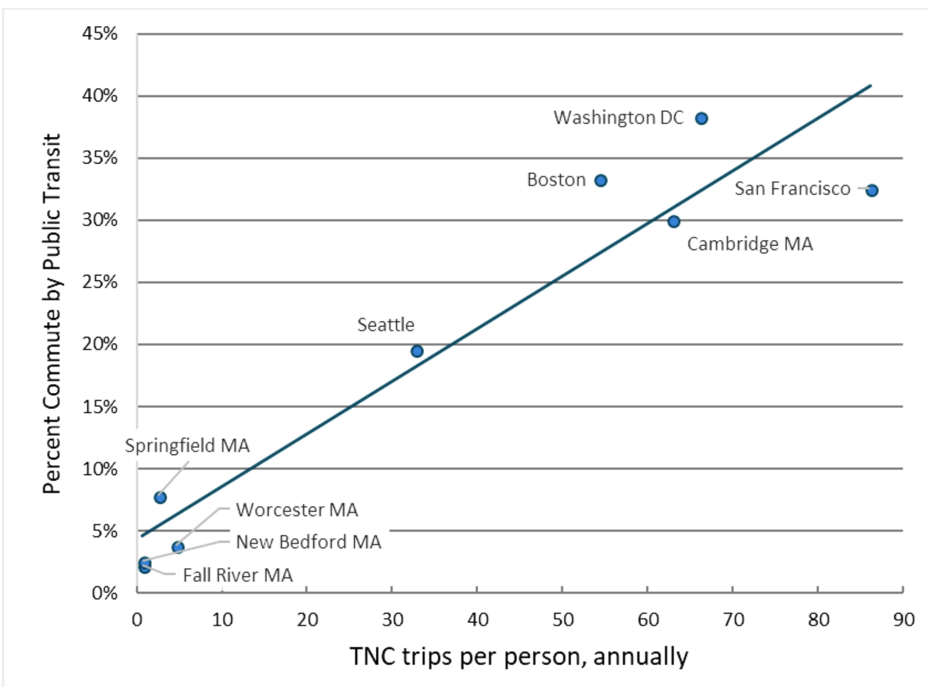
Gelauff et al. (2017) used the LUCA model to study the effects of AVs on population distribution in the Netherlands. They created various scenarios based on different levels of automation in both public transportation and personal cars. The researchers found that increased efficiency in public transit systems tended to bring more people to urban centers, while the automation of personal vehicles resulted in a shift towards suburban areas. Overall, highly urbanized regions saw an increase in population in both cities and suburbs when the impacts of both types of automation were combined, while isolated cities and their suburbs experienced a decrease in population. Furthermore, the combination of the impacts of personal cars and public transportation leads to a significant increase in the use of public transit, with the share of public transit nearly doubling compared to the reference scenario, weighing the complementary effect.

1.3. Other Implications

Schaller (2018) found that the usage of Transportation Network Companies (TNCs) such as Uber and Lyft are closely related to public transportation ridership. In cities where a larger share of commuters uses public transportation, TNC usage tends to be higher as well. This suggests that there is a significant overlap between the customer bases of TNCs and public transportation, as both modes of transportation draw from the same pool of individuals who do not rely solely on personal vehicles for transportation.

It is important to note that this section does not draw any specific conclusion regarding the relationship between AVs and public transit, whether it may be complementary or substitutive. The focus here is to highlight the potential correlation between high public transit usage and increased AV deployment. Cities with high current public transit usage may be more impacted by AVs, as TNCs may find them more favorable for AV deployment. Therefore, it is crucial to focus on these cities when analyzing the impact of AVs.

Figure 2: TNC trips per person and percent commuting by public transit, selected cities



Source: Schaller Consulting (Public transit commuters from American Community Survey, average 2011-15.)

1.4. Conclusion

It is generally believed that the adoption of SAVs, can have both substitution and complementary effects on public transit. The substitution effect occurs when SAVs effectively replace the use of public transit, while the complementary effect occurs when SAVs are used to supplement public transit, particularly for first and last mile trips connecting to public transit since it is too costly to replace the entire trip with ride-hailing. The reason there was an increase in usage on commuter rail after adoption of ride-hailing services is probably in the same context. The extent to which SAVs have a substitution or complementary effect on public transit can depend on various factors, including the size of the transit agency and city, the reliability of the transit system, and the relative cost of using SAVs compared to public transit. In general, it is more likely that SAVs will have a substitution effect when their cost is significantly lower than the cost of public transit, as people may be more likely to use SAVs to replace their entire trip. Ultimately, the level of cost reduction will determine whether SAVs are used to replace or supplement public transit.

However, it may be challenging or take a significant amount of time to reduce the cost of SAVs to the point where they are comparable to the cost of public transportation. As a result, in cities with large population, well-developed public transportation system, and large number of underutilized small agencies can potentially complement and enhance existing public transportation options. In areas where there is a significant demand for public transit but a large portion of the region is composed of areas with limited accessibility to public transit, there is a greater likelihood of deploying AVs that can have a complementary effect on public transportation. This could make underserved areas by public transportation more valuable, as SAVs could potentially fill the transportation gap in these areas. The deployment of SAVs may lead to urban sprawl due to increased accessibility, but it is possible that housing prices in urban centers will not decrease as expected due to increased demand from more people migrating to these cities. In this thesis, I will focus on the complementary impact of SAVs on public transportation, specifically during the early stages of AV deployment.

2. Application

2.1. Data and Methodology

As previously mentioned, in large cities with a higher proportion of lower levels of public transportation ridership, it is expected that the deployment of SAVs will have a complementary impact on transportation options. Also, cities with higher levels of overall public transportation usage may see a greater deployment of SAVs.

2.2. Size of the City

In their analysis of the relationship between ride-hailing services and public transportation usage, Hall et al. (2018) initially used population size as a measure of a "large city," but found that population density was a more accurate predictor of the effect of Uber on public transportation ridership. In order to accurately capture the characteristics of a "large city," I used both population size and density as indicators in my analysis. While population density is an important factor in understanding the relationship between ride-hailing services and public transportation, it is also important to consider the overall size of the city. This is because some cities may have a high population density due to their small land area, rather than being a true "large city" in terms of population size. By using both population size and density as measures, I aimed to provide a more comprehensive and nuanced understanding of the relationship between ride-hailing services and public transportation in different urban contexts.

In my analysis, I selected the top 20 cities in terms of both population size and density, but excluded New York City due to its extreme size and density. Previous research by Hall et al. (2018) has shown that the results are robust to the exclusion of New York City, and this decision is also in line with the opinion of the Brookfield Public Securities Group (2020), which stated that densely populated cities with advanced public transportation systems such as Hong Kong, Tokyo, and New York are less likely to be significantly impacted by autonomous fleets. This is due to the space constraints and availability of viable alternatives in these locations.

In order to capture the full extent of the impact of autonomous fleets on commuting patterns, I chose to use metropolitan statistical areas (MSAs) rather than individual cities as the unit of analysis. This decision was based on the recognition that the impact of autonomous fleets on commuting is likely to be felt at the MSA level, rather than being confined to individual cities.

The population data used in this analysis was obtained from the U.S. Census Bureau (2021), and specifically from the annual population estimate as of April 1, 2020. The population density data was obtained from USA.com (n.d.).

2.3. Transit Agency Characteristics

To find out cities with small transit agencies, I utilized data from the Federal Transit Administration (2021). This database includes monthly ridership data for virtually all transit agencies that receive federal funding, enabling an exhaustive analysis of public transportation usage. I specifically used the metric of "passenger per hour," which represents the average number of passengers who board a vehicle or passenger car during one hour of service.

To provide a comprehensive analysis of public transportation usage within each MSA, I included all agencies that have the same "primary UZA population", which is the population of the urbanized area primarily served by the agency. This allowed me to take into account the full range of public transportation options available within each MSA and to consider all relevant agencies. According to Hall et al. (2018), transit agencies that had below median public transit ridership experienced 6 percent increase in public transit use. Therefore, I calculated the median value of "passenger per hour" for 20 MSAs and then calculated the percentage of transit agencies below that median number, with higher percentage representing higher potential of benefiting from SAVs.

In addition to evaluating ridership levels, I also considered the number of transit agencies serving each MSA. Hall et al. (2018) found that Uber penetration tends to increase with the number of transit agencies servicing the MSA, so including this factor in my analysis was important for accurately assessing the impact of ride-hailing services on public transportation usage. To facilitate comparison across different MSAs, I normalized the data for the top 20 MSAs.

2.4. Public Transit Usage

To analyze the percentage of people commuting to work via public transportation, I used data from the American Community Survey (ACS) report for 2019. In this analysis, ACS calculated the total number of public transportation commuters as a proportion of the number of workers aged 16 years and over.

In my analysis, I assigned the greatest weight to the variable representing the percentage of people commuting to work via public transportation. This decision was based on the understanding that ride-hailing services are more likely to have a complementary impact on transportation when a significant portion of the population is willing to use them, and previous research has shown that public transit usage is strongly correlated with ride-hailing service usage.

2.5. Result

As shown by the table below, the top MSAs that are most likely to be impacted by the introduction of SAVs are San Francisco, Chicago, Boston, Washington D.C., Los Angeles, and Philadelphia. The ranking may vary depending on the allocation of weights for each variable, but the top MSAs remain the same even though their relative ranking may shift slightly. The top six MSAs have scores within a certain range, but there is a noticeable decline in the total score for consecutive cities. Our findings suggest that it is necessary to thoroughly examine the cities that are most likely to be impacted by SAVs. By studying these cities more closely, we can better understand and anticipate the potential impact of these technologies.

Table 1: The top 20 metropolitan areas that are likely to have the most impact with AV deployment

Rank	MSA	Size of the City		Transit Agency Characteristics		Public Transit Usage	Total
		Population	Population Density	Number of Agencies	% below median ridership		
Maximum		10.00	10.00	10.00	20.00	50.00	100.00
1	San Francisco	4.00	6.00	1.90	5.60	50.00	67.50
2	Chicago	8.00	4.00	1.57	11.06	40.00	64.63
3	Boston	4.00	4.00	1.65	8.79	40.00	58.44
4	Washington	4.00	4.00	1.65	7.30	40.00	56.95
5	Los Angeles	10.00	10.00	10.00	13.50	10.00	53.50
6	Philadelphia	4.00	6.00	1.16	12.23	30.00	53.39

7	Baltimore	2.00	4.00	1.07	11.31	20.00	38.38
8	Dallas-Fort Worth	6.00	4.00	1.49	16.76	10.00	38.25
9	Charlotte	2.00	4.00	0.50	20.00	10.00	36.50
10	Seattle	2.00	2.00	1.82	0.57	30.00	36.39
11	Atlanta	4.00	2.00	1.49	18.38	10.00	35.87
12	Cleveland	2.00	2.00	0.50	16.76	10.00	31.26
13	Detroit	4.00	4.00	0.08	13.06	10.00	31.14
14	Tampa	2.00	4.00	0.50	10.29	10.00	26.78
15	Phoenix	4.00	2.00	0.50	10.29	10.00	26.78
16	Minneapolis	2.00	2.00	0.74	11.58	10.00	26.32
17	Houston	6.00	2.00	0.66	4.73	10.00	23.40
18	San Diego	2.00	4.00	0.41	4.99	10.00	21.40
19	Miami	4.00	4.00	2.31	0.00	10.00	20.31
20	Orlando	2.00	2.00	0.00	3.81	10.00	17.81

III. Micro Level Analysis

1. Demand Side

1.1 Location and Housing Price

1.1.1. Rent Gradient

The relationship between the price of land and the location in accordance with the transportation cost is the basic urban economics theory that was first invented by German agricultural economist Von Thünen in 1826 (Guilford County Schools, n. d.). He assumed there are different layers of rings surrounding the city with different agricultural activities and there is a maximum price for each location that people are willing to bid for that specific activity. As you get closer to the city, the transportation cost is reduced, whereas the price of the land is increased. Farmers choose the type of agriculture that maximizes locational rent at that specific location.

William Alonso then applied Von Thünen's theory to the location of households in an urban area in 1964, followed by Edwin Mills (1967) and Richard Muth (1969). In a mono-centric city, households consider the balance between the size of their home and the cost of getting to work when deciding where to live, which leads to higher rent prices in central areas of the city where transportation is inexpensive and lower rent prices in outer areas (Liotta et al., 2022).

This theory that there is a negative relationship between rent and distance from the central business district (CBD) has been tested and supported by various studies in the real estate, urban planning, and economics literature across different cities and settings. The comprehensive research was conducted by Liotta et al. (2022), in which they tested this theory in 192 cities across the world and found that 167 (87%) cities studied shows negative rent gradient as expected from the theory: rents drop by 1.4% when one kilometer is added to the distance from the city center. However, different characteristics of cities such as coastal amenities, polycentricity, and informal housing lead to heterogeneity, so that more complex model is needed to reinforce the accuracy of the model.

To better understand the rent gradient, hedonic housing price models with other variables that affect housing prices such as structural characteristics of the housing unit and neighborhood characteristics have been used in numerous studies (Ottensmann et al., 2008). On top of that, as more and more employment opportunities in cities are moving away from the CBD, there is a growing trend of using the distance to multiple employment centers, or even to all employment opportunities, as a measure of accessibility. This is becoming an increasingly popular alternative to traditional measures of accessibility taken polycentricity into account. The measure of location also can diverge from mere distance to the CBD; alternatively, either free-flow or congested travel times to employment can be used to represent the accessibility to employment. The hedonic regression model in Indianapolis metropolitan area showed that travel times performed better than distance as a measure of accessibility, with congested travel times slightly outperforming free-flow times. Measures of location that take into account employment opportunities outside of the CBD were found to be more accurate and significant than other measures of location (Ottensmann et al., 2008).

Another way to observe the housing price in relation to location is to take a look at commute costs. Blake (2019) found out that the price difference between housing with short commutes and housing with long commutes is influenced by changes in gasoline prices, as those with longer commutes will be more affected by changes in gas prices than those with shorter commutes. The research found that for every dollar increase in gasoline prices, the median home value decreases by $329

(.143%) for every additional mile of commuting distance, or $5,184 (2.3%) on average. It shows that there is a negative relationship between housing prices and the cost of commuting.

1.1.2 Conclusion

One key takeaway from literature review is that accessibility to employment centers, as measured by short distance, short travel time, or low commute cost, has a positive correlation with housing prices in both monocentric, as measured by accessibility to CBD, and polycentric cities, as measured by accessibility to multiple employment centers. This suggests that changes in mobility, such as the adoption of AVs, can have a significant impact on housing prices by increasing accessibility and flattening the rent gradient, leading to urban sprawl.

1.2. How Shared Autonomous Vehicles Would Change Commute Patterns

It has been previously noted that housing prices can be affected by various factors, including distance, time, and cost of commuting. SAVs have the potential to impact both the time and cost of commuting, but not the distance between a person's home and place of work. In this analysis, I will examine the impact that changes in time and cost of commuting via SAVs may have on housing prices.

1.2.1. Travel Cost Reduction

AVs can be programmed to optimize their driving patterns for fuel efficiency, which can lead to reduced fuel consumption and lower operating costs.

Wadud et al. (2016) investigated the various factors that impact the energy consumption of AVs and evaluated their combined effect in a range of scenarios. They found that improving traffic flow and reducing the frequency of accidents can lead to a 2% reduction in fuel consumption due to congestion. Eco-driving practices, such as enabling regenerative braking and optimizing engine capacity, can also contribute to fuel savings, with AVs expected to achieve a 20% reduction in fuel consumption over the long term. Platooning, or the practice of grouping AVs together to reduce drag, has the potential to reduce energy intensity by 3% to 25%, depending on the type of vehicle, the amount of highway travel, and the energy required to overcome drag. AVs may also enable higher highway travel speeds, leading to an increase in energy intensity of 7% to 22%. Reducing demand for acceleration and increasing acceleration time can also result in fuel savings of 5% to 23%. Additionally, the elimination of certain safety features and the adoption of lighter vehicles may also contribute to fuel savings of up to 23%. Finally, car-sharing and on-demand mobility models may allow for more efficient allocation of vehicles to trips, resulting in fuel savings of 21% to 45%. However, these reductions in fuel consumption may be offset by changes in demand for vehicle travel. Specifically, the cost savings associated with AVs may lead to an increase in personal vehicle travel of 4% to 60%, and new user groups may also contribute to an increase in travel of 2% to 11%. In addition, the shift towards car-sharing and on-demand models may lead to a decrease in individual vehicle ownership, but this may be offset by the increased travel associated with deadheading or empty-running. Overall, the research estimates that the most optimistic scenario could lead to a 40% reduction in total transport energy demand, while the next most optimistic scenario could result in a 7% reduction. The worst-case scenario, on the other hand, is not expected to result in any change.

The efficacy of eco-driving has been supported by the research of Jayawardana & Wu (2022), who demonstrated that certain driving behaviors, such as frequent stopping and starting, slow driving on congested roads, speeding, and idling, can significantly increase fuel consumption, especially on arterial roads with traffic signals that lead to stop-and-go waves. In order to address this issue, the researchers examined the use of connected automated vehicles[1] (CAVs) as a means of control. Using various scenarios and levels of CAV adoption, the study found that the implementation of CAVs can lead to a reduction in fuel consumption. In the "vanilla" version of their study, the adoption of CAVs resulted in a 9.4% reduction in fuel consumption at the lowest level of adoption (25%) and a 18% reduction at full adoption (100%).

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[1] A CAV is a type of AV that is connected to a network, such as the internet or a dedicated short-range communications (DSRC) network, which allows it to communicate with other vehicles and infrastructure. This communication allows CAVs to share information such as traffic conditions, road closures, and other relevant data, which can improve the safety and efficiency of the transportation system.

Table 2: Comparison of fuel consumption and speed under various control strategies

CAV Penetration (%)	V-IDM		N-IDM		M-IDM	
	Fuel	Speed	Fuel	Speed	Fuel	Speed
25	9.40	9.80	7.27	7.36	12.0	12.5
50	13.4	14.4	12.9	13.2	16.3	17.8
75	15.0	16.7	16.0	17.0	22.6	26.7
100	17.8	19.9	18.4	20.6	25.5	31.9

Source: Jayawardana and Wu (2022)

According to Silberg (2014), the incorporation of AVs into car share fleets is expected to be financially viable due to the potential for reduced operating costs, specifically from a decrease in fuel consumption at 19%. This is consistent with a similar reduction in fuel consumption found by Jayawardana and Wu (2022). In addition, there is a significant reduction in fixed costs, such as depreciation and insurance, at 57%. These factors, combined with the increased prevalence of traffic and shorter commutes, are expected to make AVs a popular choice for inclusion in shared vehicle fleets.

Table 3: Predicted reduction in cost per mile

Vehicle type	Fixed costs (per mile)*	Operating costs (per mile)**	Total (per mile)
Today's car	$0.61	$0.21	$0.82
Future mobility car	$0.26	$0.17	$0.43
% reduction	57.3%	19.0%	47.6%

Source: Silberg (2014)
* Depreciation, insurance, finance, and registration- related costs   ** Gas, maintenance, and tires

In order to analyze the relationship between vehicle miles traveled (VMT) and public transit ridership, I gathered data on annual VMT and public transit ridership percentage of workers for each census tract, which is a small, relatively permanent statistical subdivision of a county defined by the Census Bureau. I obtained this data from the Center for Neighborhood Technology's (CNT) Housing and Transportation (H+T®) Affordability Index, which is a measure of the affordability of housing and transportation in a given area. I then conducted a regression analysis and found that there is a statistically significant negative relationship between travel distance and public transit usage. This result aligns with my expectations, as it is common for individuals to prefer driving over using public transit for longer distances due to decreased accessibility. Using the formula derived from this regression, I calculated the expected public transit ridership for various travel distances and identified areas where actual ridership is below this expectation. The analysis revealed that 1,784 out of 2,885 census tracts have the potential to see an increase in public transit ridership with the deployment of SAVs due to improved accessibility. These areas present opportunities for the implementation of SAVs to enhance public transit usage and potentially increase housing prices.

Table 4: The outcome of the linear regression analysis between travel distance and public transit usage

Variable	Sample Size	R square	Coefficient	Standard Error	t Stat	P-value
Intercept	2,885	0.531337	40.10891447	0.508827002	78.82623035	0
Annual VMT per household			-0.001935523	3.3849E-05	-57.18107787	0

Figure 3: The outcome of the linear regression analysis between travel distance and public transit usage

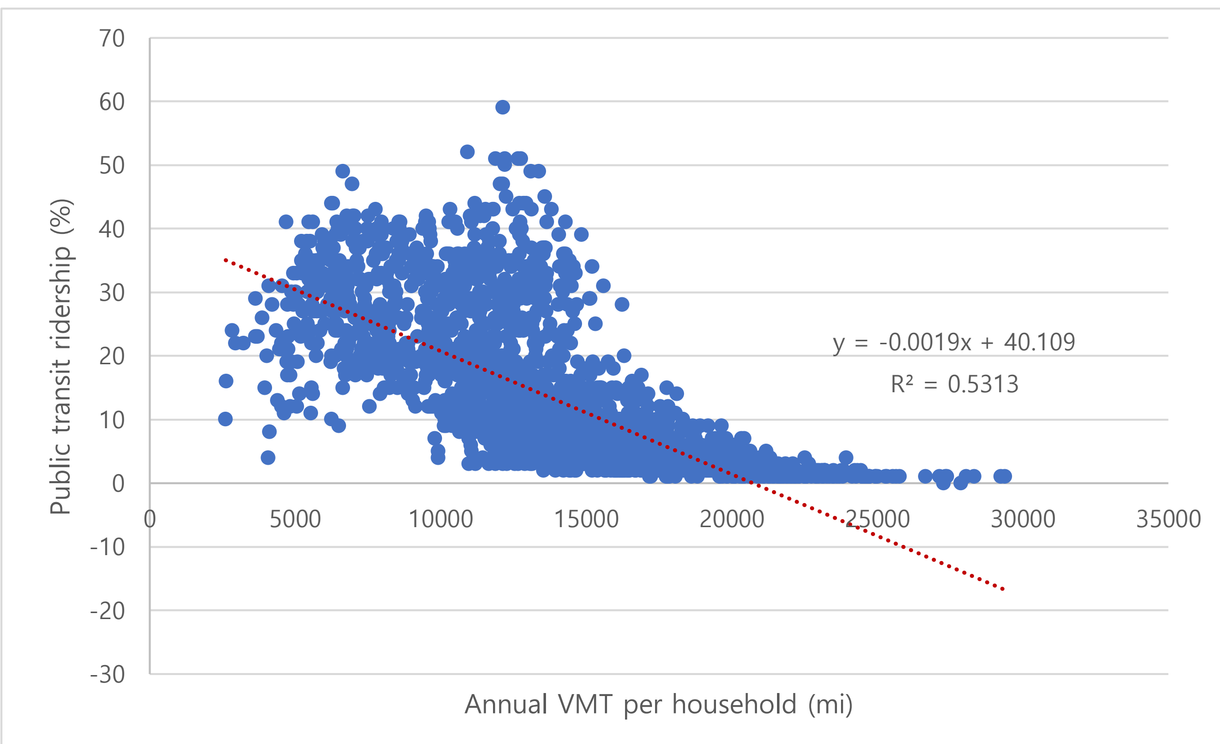
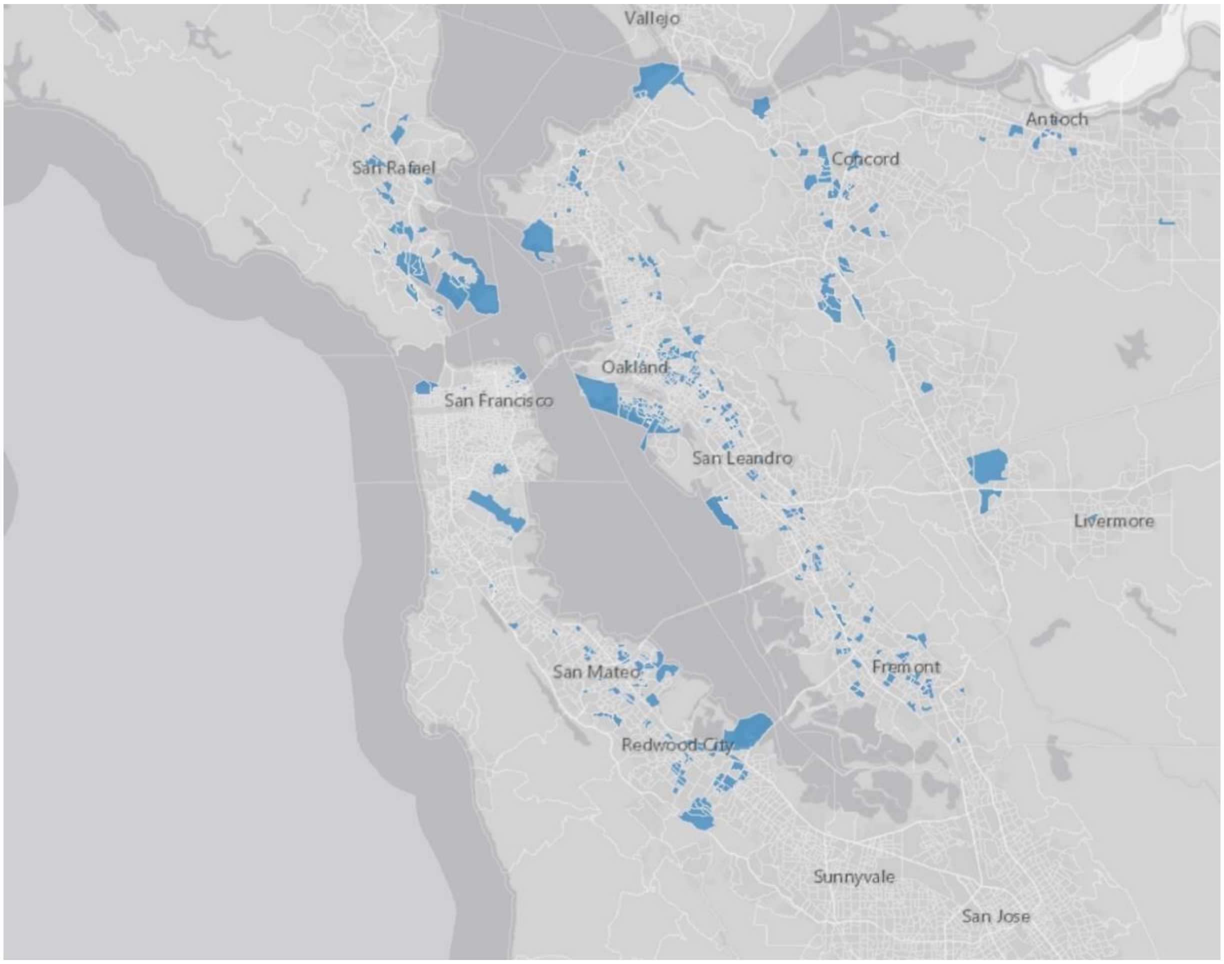


Figure 4: Areas with below average public transit ridership



To estimate the housing price change in these areas, the Blake (2019) study was used. This study involved a regression analysis to examine the relationship between housing value and distance from the workplace when gasoline prices change. The coefficient was calculated using national-level commuting data and can be used to estimate the change in housing value based on changes in distance and gas price. However, the study also compared the results to the implied discount rate, which represents the annual savings from being closer to work and not having to pay for gasoline for the commute. This discount rate was found to be similar to the national fixed mortgage rate (either 30 or 15 years), and can be used to infer that consumers consider commuting costs when making housing decisions in a rational and efficient manner. Although the coefficient for San Francisco is presented in this research, the analysis was conducted in 2016, and it may be more appropriate to use the discount rate approach to estimate the current change in housing prices in the presented areas. The discount rate approach takes into account the annual savings from reduced commuting costs to work, which can be reflected in an increase in housing prices.

Based on previous research, I estimated the potential impact of SAVs on housing prices in certain areas. I assumed a penetration rate of 25% for AVs and used estimates of reduced operating and fixed costs to calculate the potential reduction in commuting costs. I applied historical average mortgage rates to determine the potential impact on housing prices in certain census tracts, and identified areas where housing prices are expected to increase by more than 6% as a result of reduced commuting costs and improved access to public transit. The areas that were identified as potentially experiencing the most significant increase in housing prices were Antioch, Richmond, and San Leandro.

Table 5: The assumption and outcome of using the cost reduction method to estimate changes in housing prices

Assumption				Result	
AV Penetration	Fixed Cost Reduction	Operating Cost Reduction	Mortgage Rate	Average Change in Median Housing Price	Average Percentage Change in Median Housing Price
25%	28.7%	9.5%	3.67%	$22,587	3.14%

Figure 5: Areas within the San Francisco metropolitan region where the rate of housing price change is higher, as determined by the cost reduction method

Figure 5-1: The area around Antioch

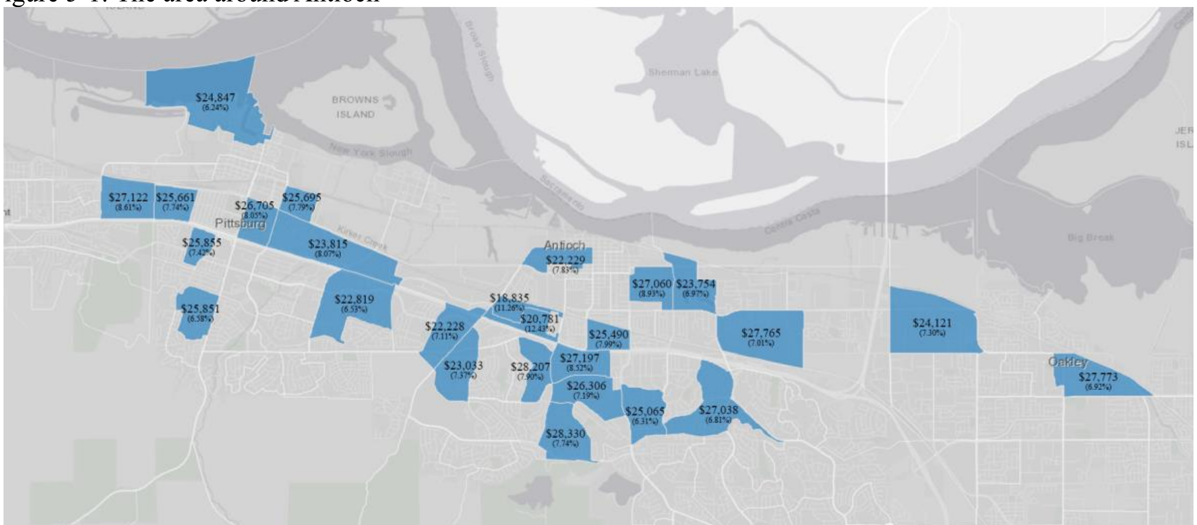


Figure 5-2: The area around Richmond

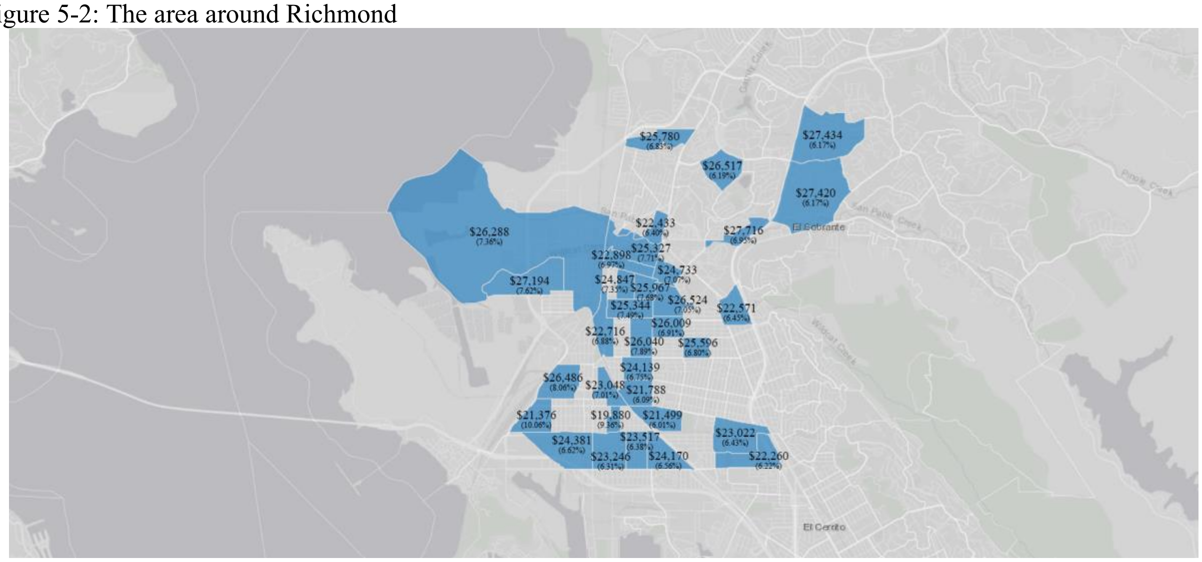
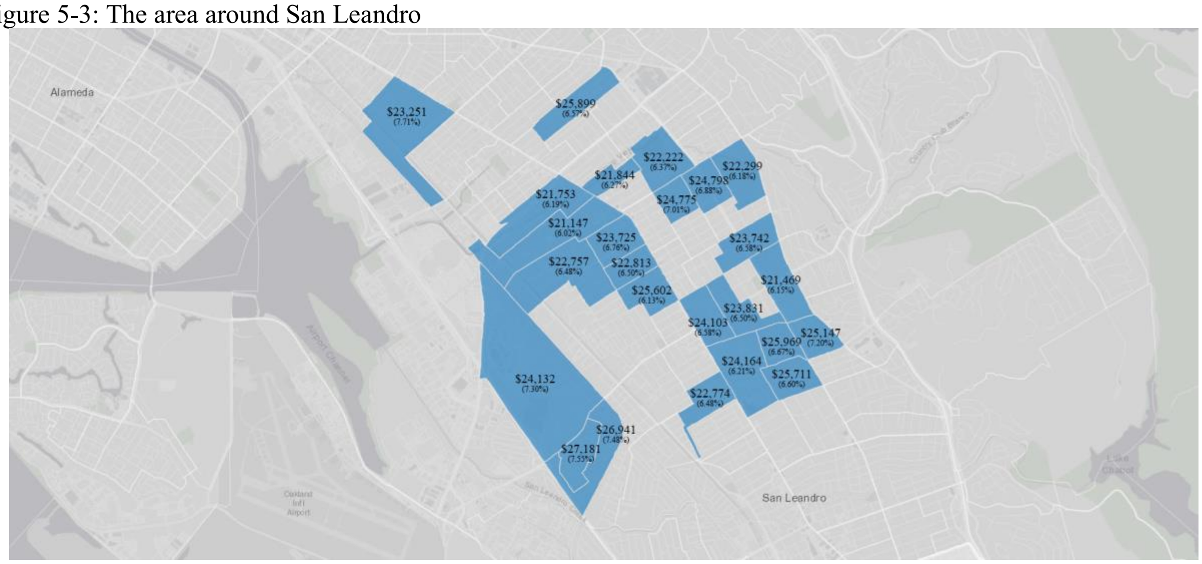


Figure 5-3: The area around San Leandro



1.2.2. Travel Time Reduction

In their study, Hamadneh & Esztergár-Kiss (2021) examined the potential for reducing travel time for various types of travelers through the deployment of AVs in Budapest, Hungary. To do this, they used travel data and the simulation tool MATSim to optimize and simulate the travel plans of individuals in the area. The groups were divided into long-distance travelers, those who relied on public transportation, and those with specific characteristics such as private car ownership or the absence of a monthly public transportation pass. The group most relevant to my analysis is public transit riders, and the scenario assumes that AVs will be used to transport individuals between the location of an activity and a public transit stop, and vice versa. AVs have the potential to significantly reduce trip duration compared to conventional modes of transportation. However, the optimized AV fleet includes a waiting time of approximately ten minutes, which results in a 33% reduction in total time savings.

Table 6: Comparing the duration of trips using traditional transportation methods versus AVs

Group	Autonomous vehicles			Conventional modes	Time-saving	
	AV fleet size	95th percentile passenger waiting time (min)	Average trip duration (min)	Average travel time (min)	(min)	(%)
Public transit riders	425	10.9	13.2	36.2	12.0	33%

Source: Hamadneh & Esztergár-Kiss (2021)

Boles (2019) conducted a study in which he collected a dataset containing various factors that may impact housing prices in San Francisco. Using single-family home listing prices as the dependent variable, he employed linear regression to identify the factors that significantly influence housing prices. After eliminating variables that were highly correlated with one another, he identified four strong independent predictors of housing prices: home size, lot size, commute time, and school scores. However, the data used by Boles was based on listing prices, which tend to be higher than the median housing prices reported by the United States Census Bureau. In order to appropriately compare the results with the commuting cost analysis, the listing prices were divided by 1.3. This adjustment was made because the average median price and listing price differed by 30%. Using the adjusted home prices, a regression analysis was conducted with the other variables from the dataset used by Boles (2019). The results were impressive, with all variables showing statistical significance. In particular, the analysis showed that commute time has a negative relationship with home price, as expected. Specifically, a one-minute decrease in commuting time was associated with an increase in home price of $10,877.

Table 7: The result of the linear regression analysis for various factors impacting housing prices

Variable	Sample Size	R square	Coefficient	Standard Error	t Stat	P-value
Intercept	5,758	0.734298	485,699	16,514	29.41125	3E-177
Home_size			354	6	63.00424	0
Lot_size			23	1	17.99909	1.65E-70
School_score			6,940	224	31.04313	9.3E-196
Commute_time			-10,877	142	-76.3456	0

To determine the potential effect of autonomous vehicles on commuting time, I assumed that the use of AVs would result in a 8.25% reduction in commuting time. This assumption is based on research by Hamadneh and Esztergár-Kiss (2021), which found that AVs can reduce commuting time by 33% when used in conjunction with public transportation. The final reduction rate was calculated by multiplying this finding by the assumed AV penetration rate of 25%. This assumption is supported by the findings of Jayawardana and Wu (2022), who also found that a 25% AV penetration rate leads to a 9.8% increase in speed. Using these assumptions, I applied a reduction of 8.25% to current commuting time and multiplied the result by a coefficient of 10,877.

In contrast to the previous analysis of the impact of autonomous vehicles on commuting costs, which was based on data for each census tract, this analysis uses city-level data for commuting time. The results show that cities with longer commuting times and lower current home prices tend to experience a higher percentage change in home prices. As was the case in the analysis of commuting costs, Antioch had the highest percentage change, and cities near Antioch had the greatest impact. Vallejo is another city that appears to have a significant impact, which was not observed in the analysis of commuting costs. However, it is worth noting that the magnitude of the change in home prices is much greater in this analysis. The average price change in the analysis of commuting time was $59,870, compared to $22,587 in the analysis of commuting costs. Additionally, the standard deviation was much higher in the analysis of commuting time. For example, in Antioch, the average change in home price was $25,138 in the analysis of commuting costs, but $114,582 in the analysis of commuting time. This may be due to the limitations of linear regression, as the model may not fully capture all of the factors that influence home prices. The R-squared value for this model was 73.4%, indicating that the model explains a significant portion of the variance in home prices, but not all of it. Including additional variables in the model may lead to a decrease in the coefficient for commuting time and a more accurate representation of the data.

Figure 6: Areas within the San Francisco metropolitan region where the rate of housing price change is higher, as determined by the travel time reduction method

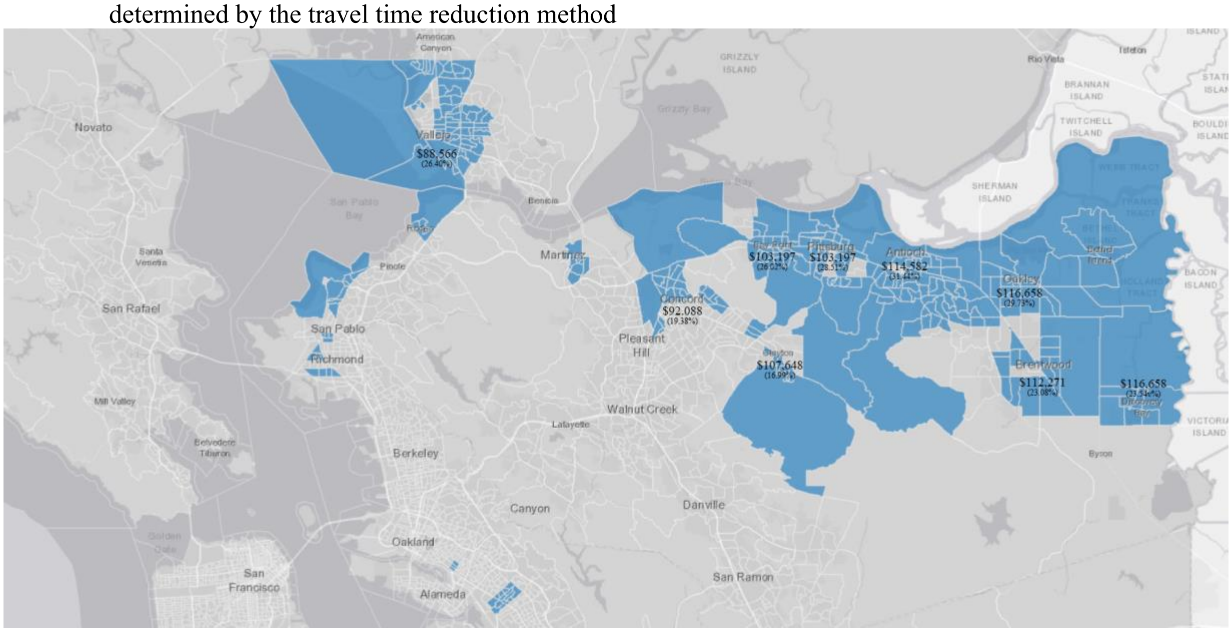


Table 8: Cities with the highest average percentage change in housing prices in the San Francisco metropolitan area, as determined by the travel time method

Rank	City	Average of Price Change	Average of Percentage Change
1	Antioch	114,582	31.44%
2	Oakley	116,658	29.73%
3	Pittsburg	103,197	28.51%
4	Spbl	80,763	28.38%
5	Vallejo	88,566	26.40%
6	Bay Point	103,197	26.02%
7	Boulder Creek	87,044	25.94%
8	Mountain House	107,684	23.58%
9	Discovery Bay	116,658	23.54%
10	Brentwood	112,171	23.08%
11	Pacheco	89,737	23.06%

12	Tracy	107,684	21.87%
13	San Pablo	80,763	21.77%
14	Rodeo	85,250	20.20%
15	Concord	92,088	19.38%

1.2.3. Conclusion

While the magnitude of housing price increases may vary due to changes in assumptions, it is more meaningful to consider the potential areas that may experience such increases. Factors such as mortgage rates and the percentage change in cost reduction can significantly impact the results of a cost reduction approach. These assumptions are based on speculative or historical data and may be difficult to project with accuracy. However, it is certain that areas with low public transit access and low housing prices are likely to experience the greatest impact on housing prices as commute costs and times decrease.

2. Supply Side

It is difficult to predict the exact effects of AVs on the supply side of the housing market. However, there is significant potential for parking lots, particularly in downtown areas with high land prices and limited housing supply, to be repurposed into housing. AVs may facilitate the removal of unnecessary parking and the redevelopment of car parks, potentially introducing new homes.

2.1. Impact on Urban Parking Spaces

2.1.1. Parking Demand Reduction

Zhang et al. (2015) developed a model to simulate the operations and interactions of SAVs and vehicle trips in an urban area using 2009 NHTS data, in order to predict the performance and benefits of a dynamic ridesharing SAV (DR-SAV) system. The model indicated that the typical household generates approximately 5.66 vehicle trips per day and owns 1.86 vehicles. With an average of 30,000 trips in the base model, the authors anticipated that the 700 SAVs would replace around 9,858 privately-owned vehicles (calculated as 30,000/5.66*1.86). The base simulation results showed that the 700 SAVs only needed an average of 3,165 parking spaces throughout the day. Given the average privately-owned vehicle in the United States requires four parking spaces, the 9,858 privately-owned vehicles in the urban area would typically require 39,432 parking spaces. The DR-SAV system eliminated approximately 92.5% of these parking spaces that would have otherwise been required for household vehicles.

According to International Transport Forum (2015), when several scenarios for the deployment of AVs were tested in Lisbon, the most favorable scenario resulted in the removal of approximately 80% of off-street parking spaces. However, with only 50% AV penetration, the reduction in parking spaces was in the range of 20% to 25%.

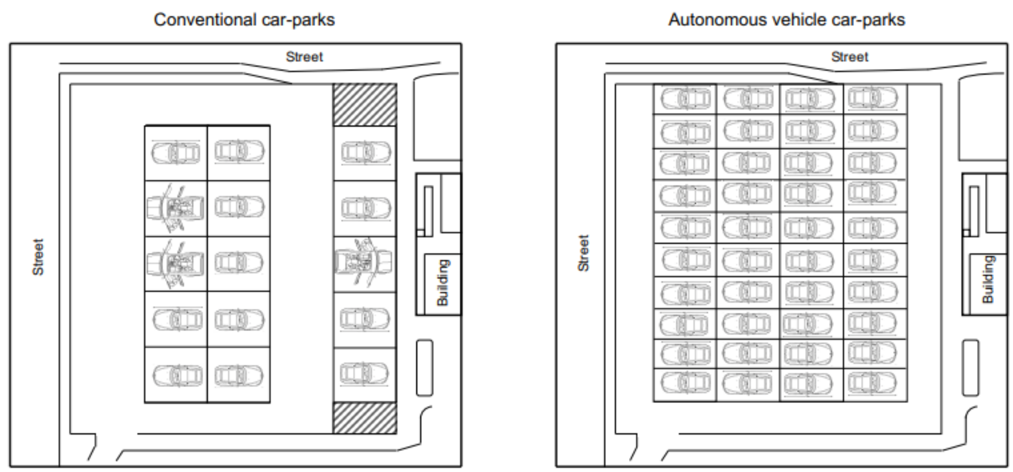
Zhang & Guhathakurta (2017) investigated the potential differences in parking demand and parking land use under free and charged parking scenarios in Atlanta. The simulation results demonstrated that when SAVs serve 5% of trips in both charged and free parking scenarios, parking land use can be reduced by approximately 4.5%. Additionally, the results revealed that each SAV can liberate more than 20 parking spaces in the city. The reduction in parking demand and land use is primarily achieved through increased vehicle utilization and a decrease in private automobile ownership.

2.1.2. Optimization of the Parking Layout

According to Nourinejad et al. (2018), the adoption of AVs has the potential to reduce the demand for parking in a number of ways. One such method is through the use of automated parking systems, in which AVs drop off passengers at a designated area and then proceed to a parking spot chosen by the car park operator. This can result in a decrease in the average space needed per vehicle due to factors such as narrower driving lanes, the removal of elevators and staircases, and the elimination of the need for space to open vehicle doors. Additionally, traditional parking facilities typically only have two rows of vehicles per island, but AV-specific designs could include multiple rows of vehicles stacked behind each other. While this multi-row design may cause some vehicles to be blocked, this issue can be addressed through proper management within the facility. Nourinejad et al. (2018) also found that AV car parks can significantly reduce the demand for parking space, with an average reduction of 62% and a maximum reduction of 87%.

The implementation of automatic parking assist systems in the market presents an opportunity for a reduction in the need for dedicated parking spaces in the near future. As these systems allow for vehicles to be parked without the presence of a human operator, a decrease in parking demand can be achieved without significant pushback. This differs from the integration of AVs on roads, which raises various safety concerns.

Figure 7: Comparison of space design for traditional parking and AVs



Source: Nourinejad et al. (2018)

2.1.3. Development Opportunities

The Audi Urban Future Initiative examined the potential impact of AVs on parking spaces in Somerville, Massachusetts. It was estimated that each parking space in Somerville could cost an average of $25,000, which could have a significant impact on the profitability of a development. To address this issue, Audi proposed designing a garage specifically for self-parking cars, which they calculated could save 62% of the subject project area, or $100 million in monetary terms (Designboom.com, 2015).

Skinner (2016) investigated the potential impact of creating an AV zone in central London, where parking coverage is currently about 16% and a total of 6.8 million parking spaces, equivalent to 8,000 hectares. The study found that the creation of an AV zone could release 50-70% of this area, or more than 5,000 hectares, and potentially increase the total developable land area by at least 15%. This would also result in cost savings as the same amount of developable land could be achieved with more efficient use of ground-level space. According to the Department for Communities and Local Government (DCLG), a 100-hectare AV zone development in central London could lead to a land value uplift of over £1.25 billion, while a similar development in outer London could result in a £300 million uplift, and developments in other parts of the country could see a value increase of £15-75 million.

2.2. Application

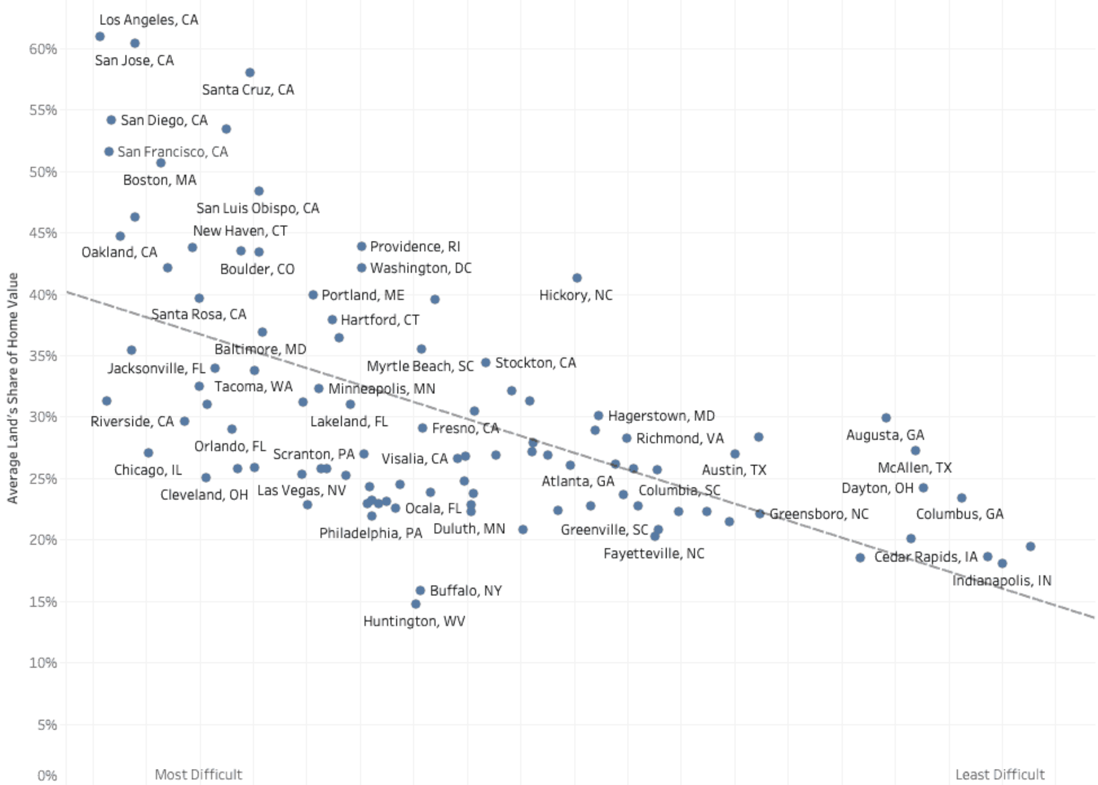
2.2.1. Excessive Parking Spaces

Chester et al. (2022) examined the parking infrastructure in the Bay Area, finding that there are approximately 15 million parking spaces for the region's 7.7 million residents, or 1.9 spaces per person. Of these spaces, 8.6 million are on-street and 6.4 million are off-street. The total number of parking spaces occupies 68,272 acres, or 1.5% of the region's total 4.4 million acres of land. However, in the 0.86 million acres of incorporated areas, parking spaces make up 7.9% of the land. The research used a coverage factor, which is the percentage of land area that is taken up by parking if all parking were surface spaces, to assess the prevalence of parking spaces. The highest densities of parking were found in the downtown areas of San Francisco, Oakland, and San Jose, with San Francisco having the highest density of off-street parking and a coverage factor of 117% in its Financial District. The median coverage factor for downtown San Francisco is 59%, dominated by non-residential land uses. There are three census blocks in downtown San Francisco where parking area exceeds land area, and at the parcel scale, there are over 3,200 non-residential and 780 residential parcels with more parking area than land area. The study estimates that, on average, there are 5.9 vehicles that need to be parked at any given time, but with 15 million parking spaces available, the utilization rate is only 39%. This suggests that there is 2.6 times more parking available across the region than is needed. The introduction of AVs may further support the conversion of parking spaces into alternative uses, as research indicates that current parking space availability is already excessive.

2.2.2. Insufficient Housing Supply

The law of supply and demand dictates that when demand for a good or service exceeds its supply, the price tends to increase. San Francisco has historically had a limited supply of housing, leading to high housing prices and affordability challenges for residents. There are several indicators that suggest San Francisco has a constrained housing supply, including its high land value as a share of home values (Glaeser & Gyourko, 2018). In metro areas where land accounts for a significant portion of home values, it can be difficult to build new housing due to a lack of available land and regulatory constraints. San Francisco has an average land share of 51.5% in home values, compared to a more affordable 20% in other areas (Bokahri, 2019).

Figure 8: Graph illustrating that the proportion of a home's value attributed to the land is higher in regions where building additional housing is difficult



Source: Redfin, The Graphic Determinants of Housing Supply (QJE, 2010)

According to Saiz (2010), the inverse of elasticity of supply, calculated using variables related to geography, regulations, and population size, correlates with housing prices. San Francisco ranked fourth among 95 metros in terms of the difficulty of increasing the housing supply due to regulatory and physical constraints; the population-weighted average elasticity of supply in metropolitan areas was estimated to be 1.75, with San Francisco's elasticity estimated at 0.66.

2.2.3. The Impact of Converting Parking Spaces into Housing

The conversion of parking spaces into housing could bring significant benefits to the housing market in Bay Area, which is currently facing supply constraints. According to the San Francisco Bay Area Planning and Urban Research Association (Fried, 2022), the redevelopment of just 1% of the region's parking area could yield over 12,000 housing units, while 5% could yield approximately 68,000 units. This is a significant increase, considering that only 20,705 units were approved in the Bay Area and 2,221 units in San Francisco in 2021 (San Francisco Planning Department, 2021). With the increasing adoption of autonomous vehicles, the excess of parking spaces is likely to increase, making the conversion of parking into housing even more viable. Additionally, the reduction of parking space requirements for housing development can lead to a decrease in housing prices. The inclusion of structured parking can add between $35,000 and $38,000 to the cost per unit, or approximately 8% of the total cost (Reid et al., 2020). This additional cost is often passed on to the overall housing price, so reducing this cost could also result in a decrease in housing prices.

IV. Conclusion

Autonomous vehicles (AVs) are a topic of increasing discussion and speculation, as many experts believe they will eventually become a common sight on our roads. Past predictions about the timeline for AV adoption have been delayed by technological and political issues, making it difficult to determine when they will become widely available. While some may be hesitant to embrace AV technology due to concerns about safety or the driving experience, it is important to consider the benefits AVs could provide to those with limited transportation options. It is likely that AVs will initially be deployed in ride-hailing services as a complement to public transit and it is worth examining the potential impacts of the initial deployment of AVs in ride-hailing services.

There is a growing body of literature examining the effects of ride-hailing services like Uber and Lyft, which can be used as a reference for predicting the impacts of AV ride-hailing services. The main difference between traditional ride-hailing and AV ride-hailing is the presence of a driver and technological advancement which significantly reduce costs. By reviewing this literature, we can identify the factors that influence the deployment of ride-hailing services and identify the metropolitan areas that are likely to be most impacted by the deployment of SAVs as part of ride-hailing services. It is expected that cities with a high population density, a large number of public transit agencies with below median ridership, and higher public transit ridership will benefit the most from SAVs by complementing existing public transit. The ranking of cities that are likely to benefit from SAVs varies based on the specific weights assigned to each factor. Upon assigning what I considered to be reasonable weights, San Francisco was ranked at the top of the list, leading me to conduct further analysis on this city. An analysis of the potential impact on housing prices in San Francisco was conducted, considering both demand and supply factors.

In the demand analysis of the impact of SAVs on housing prices in San Francisco, the historical land rent gradient model was applied. This model suggests that housing prices are influenced by accessibility to city centers or employment centers, and it is still relevant in many regions. By using this model, it was possible to predict how changes in commute costs and times due to the adoption of SAVs would affect housing prices in San Francisco. Although the magnitude of change for different areas was not consistent, some areas were identified as those most likely to experience changes in housing prices. While it may not be possible to make exact predictions about changes in housing prices, as they are influenced by a variety of factors and changes in commute costs and times are also affected by multiple factors, it is worth noting that areas with low housing prices and limited accessibility to public transit may stand to benefit the most from the adoption of SAVs.

In the analysis of the housing supply side, I considered the potential for converting excess parking spaces into housing units. This is particularly relevant in downtown areas, where the supply of housing is limited and high housing prices are driven by this scarcity. The possibility of increasing the housing supply by converting existing parking spaces into housing units or reducing the cost of housing by eliminating the need for structured parking lots could have a significant impact on decreasing housing price. However, converting garages into housing units poses several architectural and engineering challenges. For instance, parking clearances are typically lower than in houses, and the absence of plumbing and electricity systems requires additional space. Furthermore, the weight distribution of garages and housing structures differs, further complicating the conversion process. Despite the challenges that may be encountered in converting existing parking garages into housing, it is worth noting that there are various successful projects that have successfully overcome these challenges. In addition, there is already an excess of parking spaces in many areas, even without the deployment of AVs, possibly due to the previous car-ownership culture and the shift towards alternative modes of transportation. As a result, the conversion of parking spaces into housing units is a likely and imminent possibility.

Overall, considering the potential impact of AV deployment on the housing market is essential when making any real estate investment. Whether you are seeking a long-term investment or hoping to capitalize on potential price increases, it is important to be aware of how AVs may affect the market. Suburban areas with limited access to public transit may see a significant increase in housing prices, while the current high prices in downtown areas may not be sustained.

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List of Figures and Tables