The Use of Autonomous Systems in Delivering a Public Transport Service in Houston, Texas

Nikhila Krishnan

Professor John Miles

Department of Engineering
University of Cambridge

This dissertation is submitted for the degree of
Master of Philosophy

Hughes Hall August 2019

Declaration

I hereby declare that, except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 20,000 words excluding acknowledgements, declaration, appendices, bibliography, tables and equations.

Nikhila Krishnan
August 2019

Acknowledgements

I would like to thank my supervisor, Professor John Miles, for generously sharing his expertise, support, and knowledge throughout the process of creating this dissertation. Our meetings were critical in shaping my understanding of public transit planning and evaluation. I would also like to thank Elizabeth Howard for her help throughout the process. Additional thanks are extended to Dr. Stuart Scott, Kate Graham, and the Energy Technologies cohort for teaching me so much over the past year. In particular, I thank my classmates, Quentin Paletta and Chris Cantillo, for helping me proofread my dissertation. I would like to acknowledge Tory Gattis, J. Sam Lott, and Venu Garikapati for sharing their time, guidance, and Houston transport-related expertise with me throughout the dissertation process. Finally, I would like to thank my family for their enthusiasm and support during my academic career. I extend thanks to Ramesh, Sandhya, Keshav, Naveen, Jaya, Prema, Karur, Nandini, Ravi, Vinay, and Anjali Krishnan; Lee Ann, Marc, Toni, and Nicole Grossberg; Margaret Stone; Cyvia and Melvyn Wolff; Pepi Kahn; Florence and Ronald Trost; Carly, Max, and Sadie Oreck; Alison and Binah Stern; and Hector, Humphrey, Davina, and Bertie Butler. I also acknowledge my sister's fiancé, Graham Bayley, for sharing his finance expertise while helping me create financial models.

Abstract

Fast, low-emitting, and cheap public transportation systems are essential for major cities worldwide to thrive. Houston is a vibrant and rapidly expanding city with a wealth of jobs and opportunities. Despite its position as a promising major city, Houston lacks effective public transit and the majority of its citizens rely on cars for mobility. Transportation costs individual Houstonians hundreds of hours, thousands of kilograms of carbon dioxide emissions, and thousands of dollars each year. Houston needs a modern solution to transform its public transportation system, support its expected growth, and increase the quality of life for its citizens.

Autonomous vehicles have the ability to transform public transportation by encouraging the move from a system with a small number of fixed-route, fixed-timetable vehicles to a system boasting a large number of demand-responsive vehicles that provide a better service through frequent trips and end-to-end mobility solutions. They serve as a possible forward-thinking solution that can potentially reduce costs, emissions, and journey times.

This dissertation postulates the use of autonomous systems as a means of delivering a new type of public transport service in Houston and assesses the credibility of the concept against the objective sustainability criteria of social, financial, and environmental performance.

This work follows a distinct methodology to explore autonomous vehicle use through multiple applications across the Houston network. For the different applications, the demand is defined, existing public transit is investigated, performance and service level targets are set, routes and infrastructure are determined, the fleet is defined, the economics are estimated, and the emissions are calculated. This methodology is applied to the different areas of Houston including the Texas Medical Center, Downtown, and the commute form the suburbs to central Houston.

Results suggest that autonomous transport systems have great potential in Houston with regards to social, environmental, and financial standards. Autonomous systems have the potential to provide faster services (including wait times, in-vehicle travel times, and walking times), reduce emissions (in 2/3 of the cases), and be self-financing even if priced at existing public transport fare prices (assuming they pass certain ridership thresholds).

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Nomenclature

Acronyms / Abbreviations

ft^3 Cubic Feet

AADT Annual Average Daily Traffic

AV Autonomous Vehicle

BTU British Thermal Unit

CBD Central Business District

DARPA Defense Advanced Research Projects Agency

DHV Design Hour Volume

ft/s Feet per Second

gCO_2e Grams of Carbon Dioxide Equivalent

HOV High Occupancy Vehicle

km Kilometer

kWh Kilowatt Hour

kW Kilowatt

m/s^2 Meters per Second Squared

MBTU Million British Thermal Units

METRO Metropolitan Transit Authority of Harris County

min Minute

m Meter

mph Miles per Hour

pph People per Hour

SE lot South Extension Lot

TMC Texas Medical Center

Chapter 1

Introduction

1.1 Need for Public Transportation in Houston

The Greater Houston Metro Area is home to 7 million inhabitants, making it the fourth most populous city in the United States [1] [2]. It has seen the fastest growth out of any American metro area in the past 25 years and is projected to grow to 10 million inhabitants by 2040 [3] [4]. Central Houston is not only a residential city, but also a major employment center, hosting 3.1 million jobs [2] [5]. Four of the employment districts within central Houston make the list of the top 15 central business districts (CBDs) in the United States [6]. In order to continue to grow and thrive, Houston needs an effective public transit system.

A sprawling city of 1,700 square kilometers, Houston's population is sparsely distributed, with a population density of 4,000 people per square kilometer [7] [8]. Chicago, the third most populous U.S. city, has a population density 3x that of Houston's [9]. Due to the distributed nature of the population, traditional forms of mass transit such as rail or subway have limited use. Therefore, cars are the dominant form of transportation and Houston is categorized as an "automobile city" where only 2.4% of Houston commuters use public transport, while most others drive [10] [11]. Population density and transport-related energy consumption per capita are inversely related, illustrated by the Newman and Kenworthy hyperbola in Figure 1.1 [10].

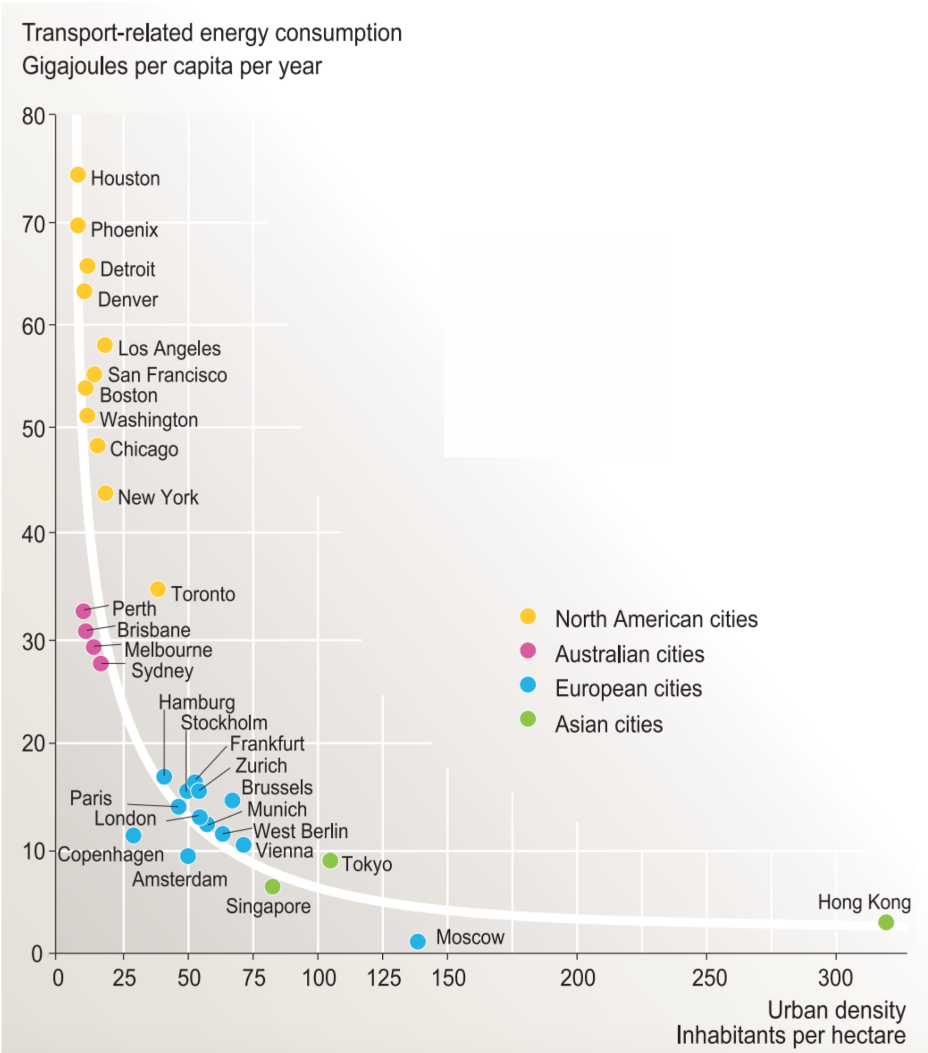

Fig. 1.1 Population Density and Transport-Related Energy Consumption [10]

Public transportation systems must adapt to serve different types of communities, not just densely populated mega-cities. This way, Houston can switch from an "automobile city" to a public transit city.

Houston's reliance on automobiles leads to a variety of negative consequences including high emissions, air quality issues, traffic, lost time, high costs, and a reduction in safety. As seen in Figure 1.1, Houston has the highest transport-related energy consumption per capita of all major cities worldwide [10]. In addition, Texas is the state with the highest absolute emissions [12]. Houston leads the cities in Texas with the highest emissions per capita, 48% of which result from the transportation sector, illustrated in Figure 1.2 [13].

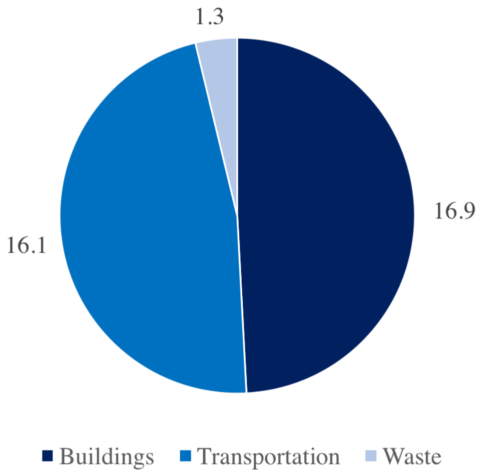

Fig. 1.2 Houston 2014 Emissions Breakdown by Sector (million metric tonnes CO_2e) [13]

In addition to carbon dioxide emissions, passenger vehicles emit methane, nitrous oxide, and hydrofluorocarbons [14]. Along with greenhouse gases, Houston's air also hosts high levels of particulates and ozone, leading to degraded air quality for 85 days in 2016 [15]. This puts millions of people at risk of asthma attacks, cardiovascular disease, and even premature death [15]. In addition, it is extremely time-consuming and expensive for commuters to travel to work. The scene in Figure 1.3 is common for Houston's highways.

Fig. 1.3 Typical Houston Highway During Rush Hour [16]

Houstonians have one of the longest commutes in the Unites States, averaging at 59 minutes round trip [17]. The average one-way distance travelled is 12.2 miles, the second-longest commute by distance in the country [18]. This means that Houston drivers lose 10 days each year just to driving [18]. Houstonians have the second most expensive commute in the nation, spending $174,000 over their lifetime on fuel and vehicle costs [19]. Finally, Houston's roads are the deadliest in the nation with 640 deaths each year due to road related incidents [20]. Studies show that 90% of car accidents are caused by human error [21]. Effective public transport can mitigate emissions, increase public health, and save commuters time, money, and possibly their lives.

A public transportation solution is necessary to support Houston's position as a major city. A METRO survey shows that "Houston-area residents, whether they live in the urban core, a city neighborhood, or a suburb, want fast, efficient, affordable mass transportation [22]." In addition to a cry for public transit from its inhabitants, many prominent members of Houston's community have expressed the need for a public transit system. According to Bob Harvey, the President and CEO of the Greater Houston Partnership, "moving Houstonians to and from work no matter where they are in the region, is essential to the upward mobility of our people and ultimately, Houston's success as a great global city [22]."

A mass transit system should be planned with three considerations in mind: the social, environmental, and financial impact of the system.

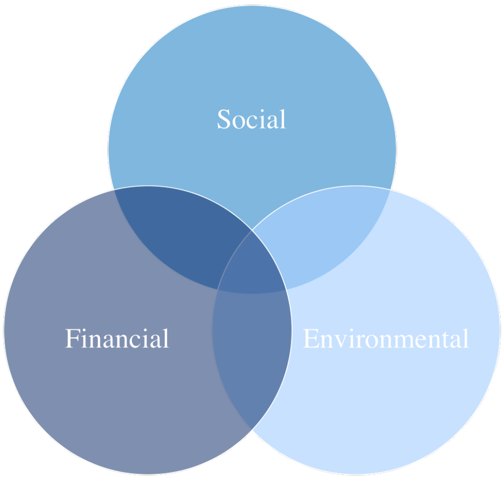

Fig. 1.4 Public Transit System Considerations

In order to encourage commuters to eschew private car use, a public transit system must be more attractive than car travel. This requires certain social benefits from the system: frequent options, quick journeys, decreased congestion, and the ability to take the traveler from point A to point B. For this project to be realistic, it must be low cost both for the

City of Houston and for commuters. Finally, the new system must help in the fight to mitigate climate change and therefore should decrease emissions compared to the current transportation system.

There are different choices for a system: traditional bus, rail, or forward-looking autonomous systems. This dissertation investigates the potential for autonomous systems to deliver a new type of public transport service in Houston, and assesses the concept against the sustainability criteria of social, financial, and environmental performance.

1.2 Current and Proposed Public Transport in Houston

Current Public Transit

Houston currently has many different public transit modes: 23 miles of light rail traversing central Houston, 1,200 buses across greater Houston, and 28 different Park & Ride routes for commuters traveling from the suburbs to central Houston [23][24]. Most of these transit options, which will be discussed in more detail in subsequent chapters, are owned and operated by the Metropolitan Transit Authority of Harris County (METRO). Despite the wide variety of transportation options, the transit system is far from a success, with only 2.4% of Houstonians using public transit to commute to work [11]. For this, Houston has been spending time, money, and effort to explore ways to expand and better the public transit system.

Proposed Public Transit

Houston METRO has proposed the MetroNext Moving Forward Plan to improve public transport in Houston [4]. The plan aims to increase connectivity, reduce travel times, incorporate advanced technologies, and enhance customer experience [4]. This plan proposes spending $7.5 billion to expand upon traditional transport infrastructure such as light rail, buses, park & rides, and bus rapid transit [25] [4].

Though the plan does not mention autonomous vehicles (AVs), self-driving vehicles could help METRO reach all the goals outlined. METRO's plan takes place in 4 stages: draft a rough outline, receive public feedback, revise based on the feedback, and implement the final plan [4]. Though this plan is to be implemented by the year 2040, the infrastructure invested in will last for decades longer. For this, the plan must be forward-thinking, investing in infrastructure that people will use a century from now. Because autonomous technology has the ability to transform the transportation sector, AVs should be considered when planning the future of Houston transit systems. This dissertation will explore the possibility of autonomous systems as a means of public transit in Houston. The goal is to present the results to Houston METRO, the City of Houston, and other influential groups to encourage the consideration of autonomous vehicles in transport planning, specifically for the MetroNext plan.

1.3 Changing Nature of Public Transportation

Until recently, mass transportation systems relied upon technology created decades or even centuries ago. Most public transit systems integrate rail, light rail, metro cars, trams, and buses [26]. The newest of these technologies is light rail, introduced in the United States in 1972 [27]. This stagnation in innovation has ended with the influx of new technology in the transportation sector. Autonomous and connected vehicles will irrevocably alter the nature of public transit.

Role of Autonomous Vehicles

Autonomous vehicles hold the key to transforming public transport. AVs can serve first mile/last mile needs; offer frequent, small services; and provide flexible, demand-responsive services. The first/last mile of transit refers to the beginning (first mile) and end (last mile) of an individual journey. There is often limited connectivity between an individual's initial location and the transit pick-up or between the transit drop-off and their intended destination. This can prevent commuters from using public transit if they have no easy way of getting to and from the transit system. Because AVs can be applied to the first/last mile of transit, they can attract more users who previously did not have convenient access to existing transit systems. This would help create a fully integrated and accessible system that can get a user from point A to point B. Because they do not require a driver, AVs allow for frequent small services. This transforms the transportation system from one with a small number of large vehicles to one with a large number of small vehicles. More frequent services reduce commute times and increase convenience. The advantage of private cars is that one can hop in a car and get wherever they want whenever they want. If a public transportation system is comprehensive so that commuters can get from anywhere to anywhere with short wait times, it can challenge the dominance of cars and thus change the face of transit with a big impact for the people of Houston.

1.4 State of Autonomous Vehicles

History of Autonomous Vehicles

Autonomous vehicles are poised to change the landscape of the transportation system. Only 8 decades ago, the idea of AVs would have been considered science fiction. An AV refers to a vehicle capable of driving itself without the control of a human driver [28]. This idea was first showcased in 1939 by General Motors at the Futurama exhibit [29]. Research continued over the next couple of decades, picking up more traction in the late 1970s when a Japanese laboratory group built an AV with image processing [30]. The idea became more mainstream in the mid 1980s when university research groups and some automotive companies began to seriously research the possibility of self-driving vehicles [30]. In 1995, Carnegie Mellon University and Bundeswehr University Munich demonstrated vehicles capable of steering themselves for 98% and 95% of the journey respectively [30]. The U.S. Defense Advanced Research Projects Agency (DARPA) hosted its first Grand Challenge in 2004 for universities or companies developing AVs to showcase their technology and compete against other groups with the goal of "spurring on American ingenuity to accelerate the development of autonomous vehicle technologies" [31]. Though no team successfully completed the course, five teams completed the following year's Grand Challenge course with Stanford's team winning first place [30]. Now, many companies have joined academics in the field of AVs.

How it Works

AVs use a "sense-plan-act" technique to perform the task of driving [30]. The vehicles have a suite of advanced sensors to "see" the environment around them, plan their actions based on the environment, and then execute the action [30]. Autonomous vehicles have many advantages over human drivers, but there are also many challenges associated with the sense portion of AV technology, summarized in Figure 1.5.

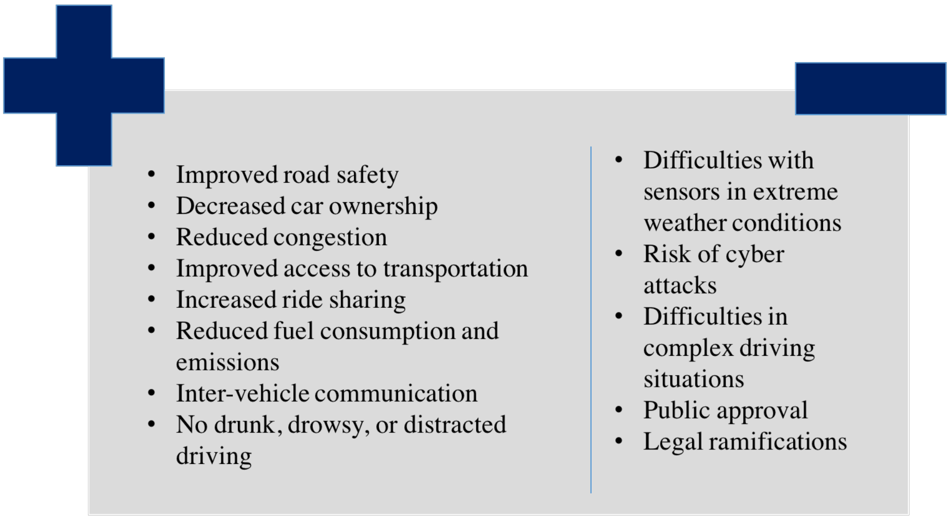

Fig. 1.5 Benefits and Challenges of Autonomous Vehicles [30][32]

There are different levels of automated driving, ranging from no automation (level 0) to high automation where the system can perform the dynamic driving task even if the operator fails to intervene (level 4) to full automation that can perform the dynamic driving task without the need for human intervention (level 5) [33]. The dynamic driving task is defined as "all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions such as trip scheduling and selection of destinations and waypoints" [21]. Figure 1.6 details the different automation levels.

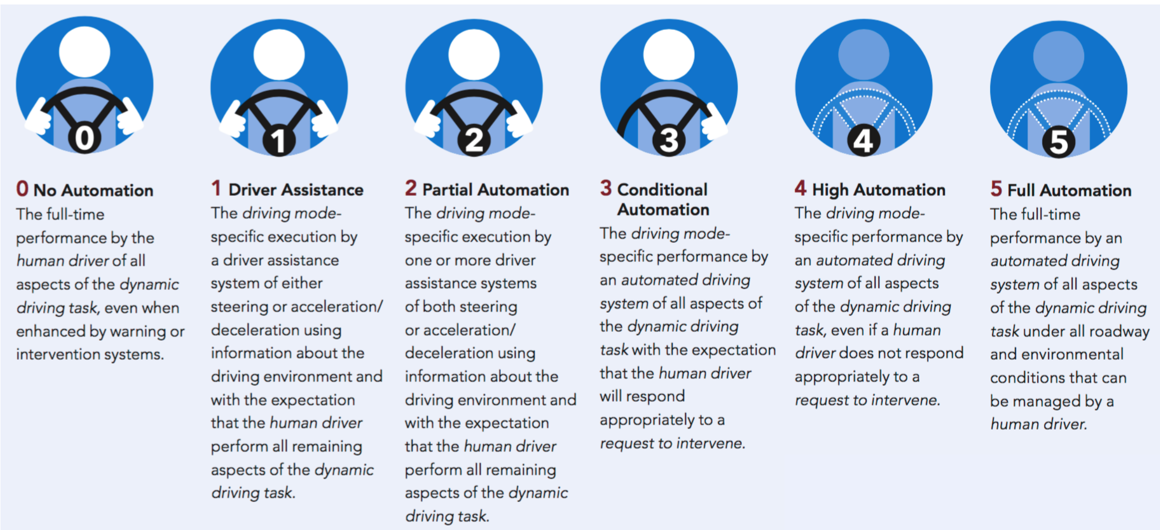

Fig. 1.6 Levels of Vehicle Automation [21][33]

This report focuses on level 4 automation because the vehicles have remote operators, whose job is to intervene if necessary. In addition, the vehicles in this report are segregated from normal traffic. This means that they will be safer, less technologically challenging, and sooner to market than level 5 automation.

Company Involvement

Many notable companies in the self-driving car space are Waymo, Uber, Lyft and almost every major car company including Ford, GM, Toyota, Audi, BMW, and Tesla [34–42]. Investors are pouring large sums of money into the field of AVs. Investments in AV technology doubled from 2016 to 2017, with over $1.4 billion dollars invested in the second quarter of 2017 [43].

Policy Overview

The United States ranks fourth on KPMG's AV readiness index [44]. Though the U.S. hosts the leading AV companies, it falls behind other countries because it lacks a comprehensive federal approach to AV adoption [44]. Policy affecting autonomous vehicle adoption is mostly determined at the state, rather than the federal, level. This can work in Texas' favor because Houston can act as a pioneering city in the field of AVs without waiting for the other 49 states to agree upon AV legislation. To date, 29 states have enacted AV legislation, including Texas [45]. Texas has passed two bills, one of which was passed in May of 2017 allowing autonomous vehicles to be operated on Texas roads without human drivers [45][46].

Houston can forge the path ahead for AV systems. The four measures for KMPG's AV readiness index are legislation, infrastructure, technology, and consumer acceptance [44]. Houston is the ideal AV testing-ground because it checks all 4 boxes. Texas has legislation allowing AVs on its roadways, Houston's highways already have AV infrastructure in the form of barrier-separated lanes on the highways, the major AV technology companies are headquartered in the United States, and a lack of an efficient transit system leads to demand for an alternative.

Houston AV Pilot

The Texas Innovation Alliance is currently piloting an autonomous shuttle system at the Texas Southern University Campus [6]. This pilot is sponsored by all the influential Houston transport organizations: METRO, the City of Houston, the Houston Galveston Area Council, Texas Southern University, University of Houston, Gulf Coast Rail District, the Texas Medical Center, and Harris County [6].

The vehicle is an EasyMile Gen-2 shuttle that acts as a university circulator, shown in Figure 1.7 [47]. This shuttle has achieved level 4 automation, fits 12 people, runs at 25 mph, and is a possible solution to the first mile/last mile problem of transit [6] [48].

Fig. 1.7 EasyMile Gen-2 Shuttle[49]

The goal of the pilot is to test the shuttle system in increasingly more complex environments before expanding it to other areas of Houston [6]. It initially will be a fixed-route shuttle in a pedestrianized area before proving itself capable of navigating mixed-traffic urban streets composed of pedestrians and other vehicles [6]. METRO's ultimate goal is to expand this AV system to all major CBDs of Houston, including the Texas Medical Center and Downtown, discussed in Chapters 2 and 3 respectively [6].

Recent Milestones and Projected Timeline

The timeline of important recent milestones in autonomous driving is shown in Figure 1.8.

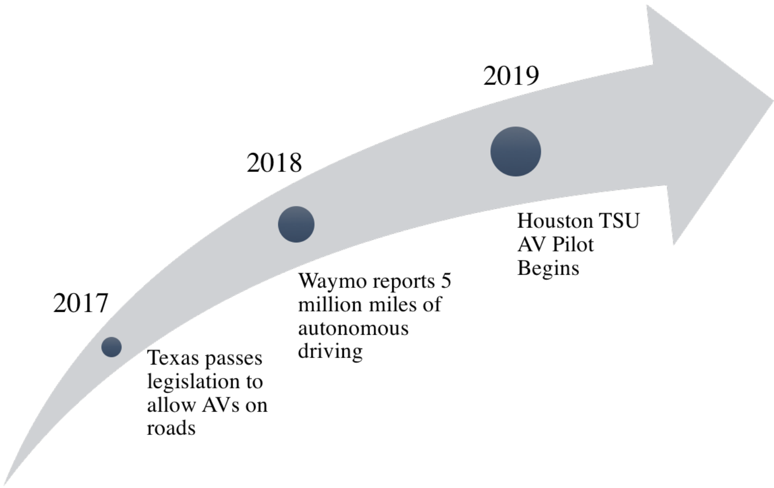

Fig. 1.8 Recent AV Timeline [34] [6] [46]

This timeline does not end in 2019. The upcoming years will see the commercial availability of AVs. BMW and Ford claim that they will reach level 3 and level 4 automation respectively for commercial viability by 2021 [41] [37]. Level 5 AVs are expected to be on the market by 2025 [50]. Thought-leaders predict that almost all road vehicles will be autonomous by 2050 [32]. The projected timeline is presented in Figure 1.9.

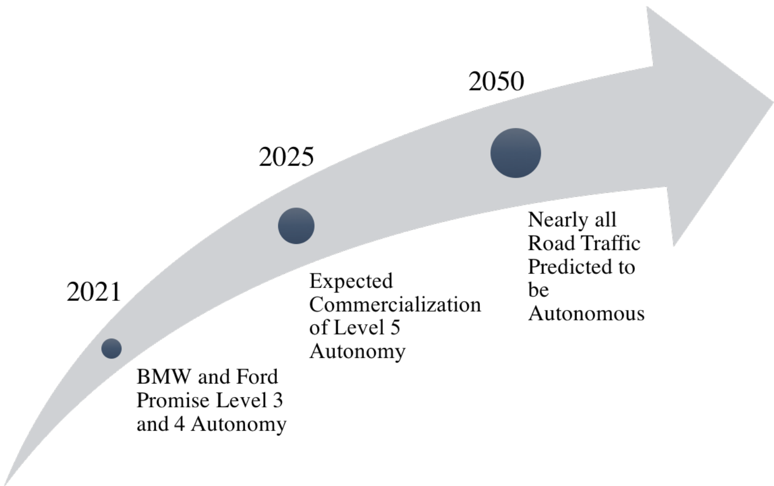

Fig. 1.9 Projected AV Timeline [41] [37] [46] [50] [32]

The proven AV shuttle systems operate at low speeds (25 mph) with dedicated guideways or within pedestrian areas. Future systems must be able to operate in mixed-mode environments at faster speeds in order to be viable, large scale systems. The estimated date for these high-speed, urban environment systems is 2022-2025 [51].

Many companies have already created AVs themselves and are testing them on public roads. This report will cover three types of AVs: small, medium, and large vehicles, described in Figure 1.10.

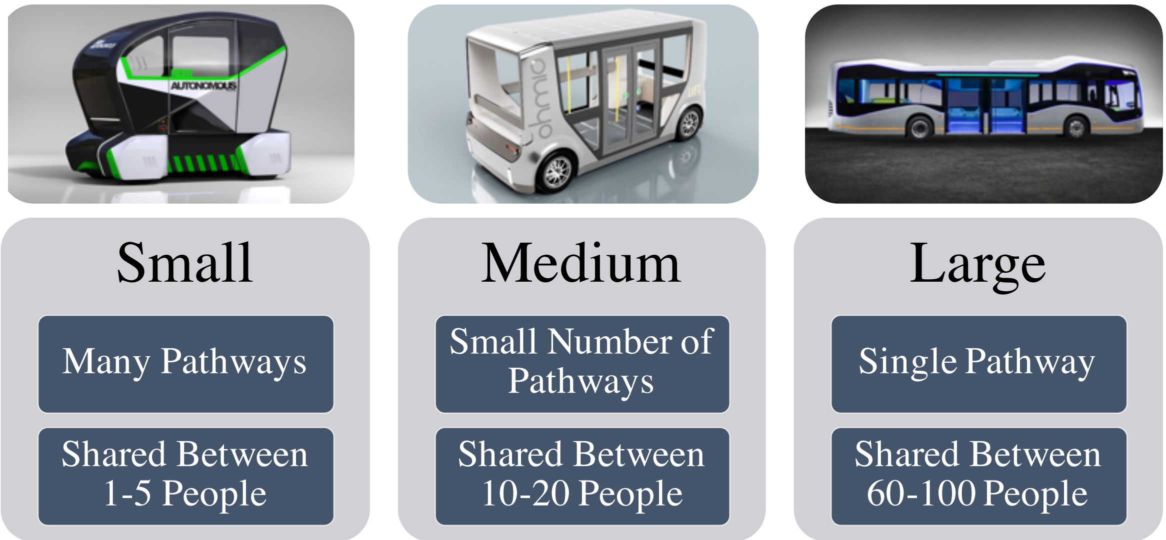

Fig. 1.10 Types of Autonomous Vehicles for Different Transit Needs [52] [53] [54]

1.5 Approach to the Problem

To replace cars, an alternative transit system must provide a point A to point B service. Therefore, the problem has three steps: first mile, transit to central Houston, and last mile. The first mile portion consists of commuters traveling from their homes to their neighborhood transit center. They subsequently are transported from the suburbs to central Houston. The last mile portion consists of the final leg of the journey in which commuters are transported to the door of their workplace. This process is summarized in Figure 1.11.

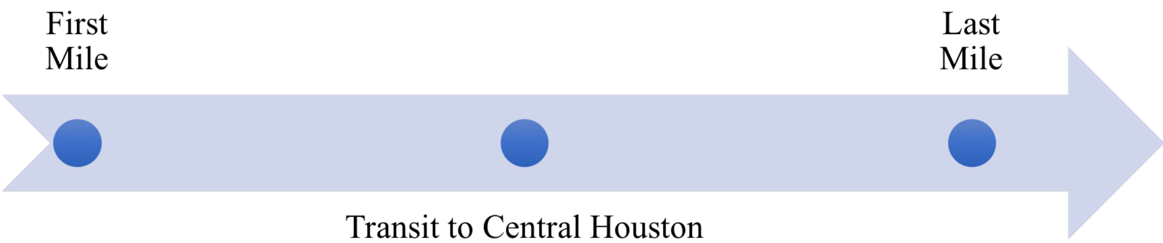

Fig. 1.11 Three Distinct Steps for a Comprehensive Transit System

1.6 Methodology

Chapters 2, 3, and 4 will follow the methodology outlined below:

1. Define the demand
2. Examine existing transport options
3. Set performance/service level targets
   (a) Capacity
   (b) Journey time
   (c) Frequency
4. Define routes and infrastructure
5. Define vehicle fleet
   (a) Vehicle size
   (b) Number of vehicles
6. Estimate economics
7. Calculate emissions

1.7 Goal of Dissertation

This dissertation explores the potential for autonomous vehicles to provide a next-generation solution to Houston's urban mobility problems. It assesses the social, environmental, and financial viability of an autonomous transport system. The dissertation explores transport within central Houston before extending to the suburbs; it starts with the last mile before describing transit to central Houston and finally the first mile. The next two chapters cover the last mile solution. Chapter 2 addresses the Medical Center while Chapter 3 covers Downtown. Chapter 4 describes the mode of transit to central Houston, Chapter 5 describes the first mile, Chapter 6 gives a sustainability analysis of the integrated transport system, and Chapter 7 presents a summary of findings and concluding remarks.

Chapter 2

Last Mile: Texas Medical Center

2.1 Texas Medical Center Overview

The Texas Medical Center (TMC) is home to the world's largest medical complex and is classified as the 8th largest business district in the United States [55]. Located in central Houston, TMC comprises 2.1 square miles [55]. Its campus geography and location on the Houston map are shown in Figure 2.1.

TMC employs 106,000 people in over 42 institutions while boasting 10 million patient visits each year [55] [56]. The efficient movement of people is necessary to support the thousands of employees and patients entering and exiting the medical center each day. For this, transportation is a key ingredient in the functionality of the medical center.

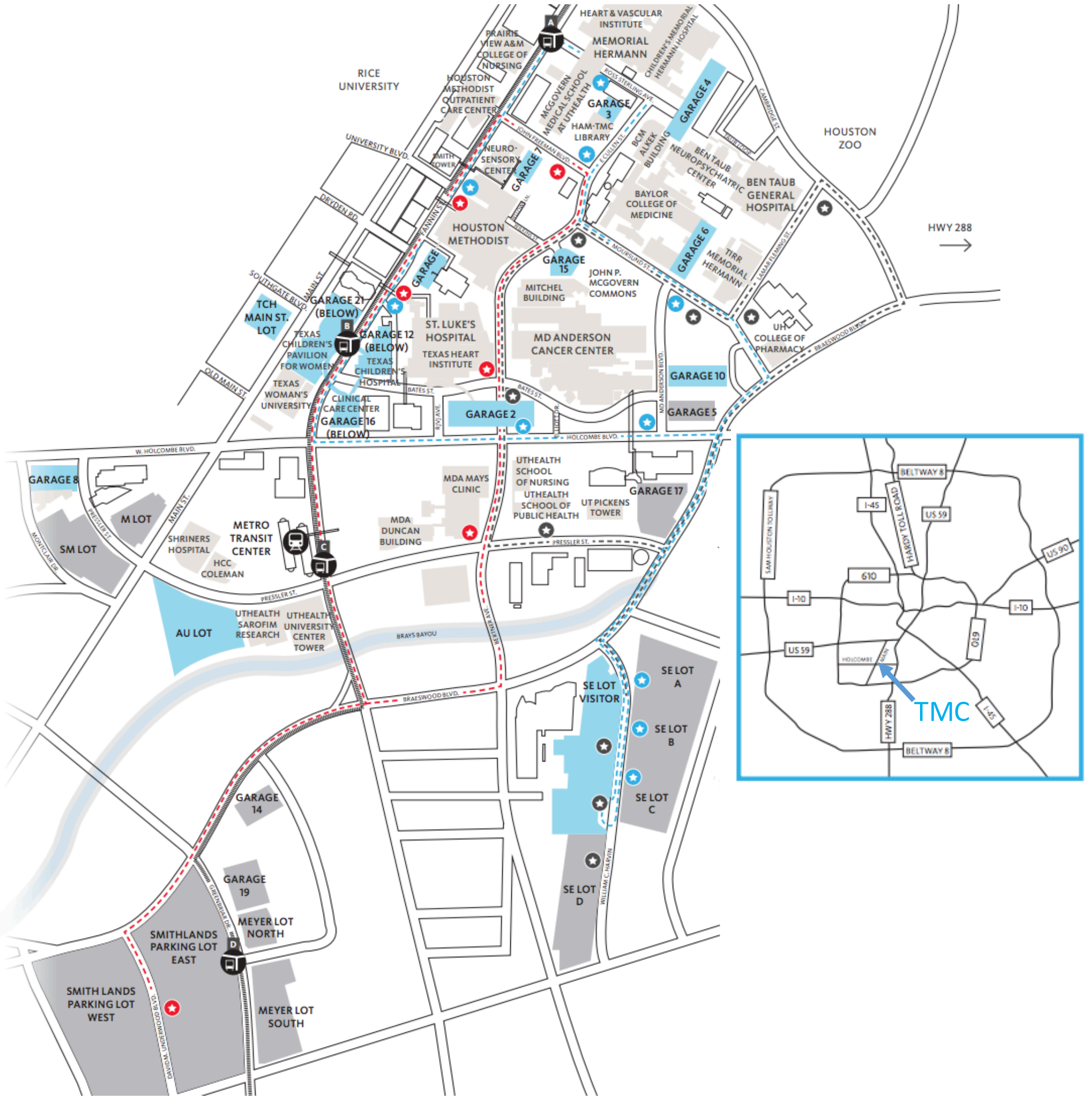

Fig. 2.1 Texas Medical Center Campus Geography and Location on Map of Houston [57]

2.2 Demand

To plan a transport system, the demand must first be quantified. Currently, many Medical Center employees drive to work and park in the Smith Lands or South Extension (SE) parking lots located on Old Spanish Trail, approximately 1.5 miles from the heart of TMC [58] [59]. It was assumed that employees need transit from the parking lot to their workplace in the morning and from their workplace to the parking lot in the evening. This report examines the AM demand. To estimate the daily AM demand for the AV system, it was assumed that each parking spot corresponds to one employee needing transit from the parking lot to their workplace. The Smith Lands and the South Extension lots provide approximately 8,000 total parking spots, so the AM demand was assumed to be 8,000 riders [59].

2.3 Existing Transport Options

Currently, to travel the 1.5 miles between the parking lot and their workplace, employees ride the Medical Center-operated shuttle system or the METRO-operated light rail line [57][60].

2.3.1 Shuttle System

Of the employees that park at the Smith Lands or South Extension lots, 33% use the free shuttle system, pictured in Figure 2.2. [61] [57].

Fig. 2.2 Texas Medical Center Shuttle

TMC operates three different shuttle routes: red, white, and blue [57].The ridership data for the three shuttle lines is summarized in Table 2.1.

Table 2.1 Texas Medical Center Shuttle System Ridership Data [61]

Vehicle	Average Weekday Ridership
Red Shuttle	1,000
White Shuttle	3,600
Blue Shuttle	800

The shuttles service employees who park in the farthest lots, the Smith Lands and SE lots [57]. The remaining employees park in the additional 15 contract parking lots and garages scattered throughout the Medical Center campus, depicted in Figure 2.1 [62]. The transit system was developed for the Smith Lands and SE lots because they are the biggest and farthest away (and therefore have the highest demand for a last-mile transit system). This chapter explores an autonomous system that services these two lots, which could later be expanded to service all lots.

The red line picks up employees from the Smith Lands lot, while the white and blue lines pick up employees from the SE lot [57]. All three shuttles travel along fixed routes through the heart of the Medical Center, stopping at many different locations [57]. The shuttle routes are shown in Figure 2.3.

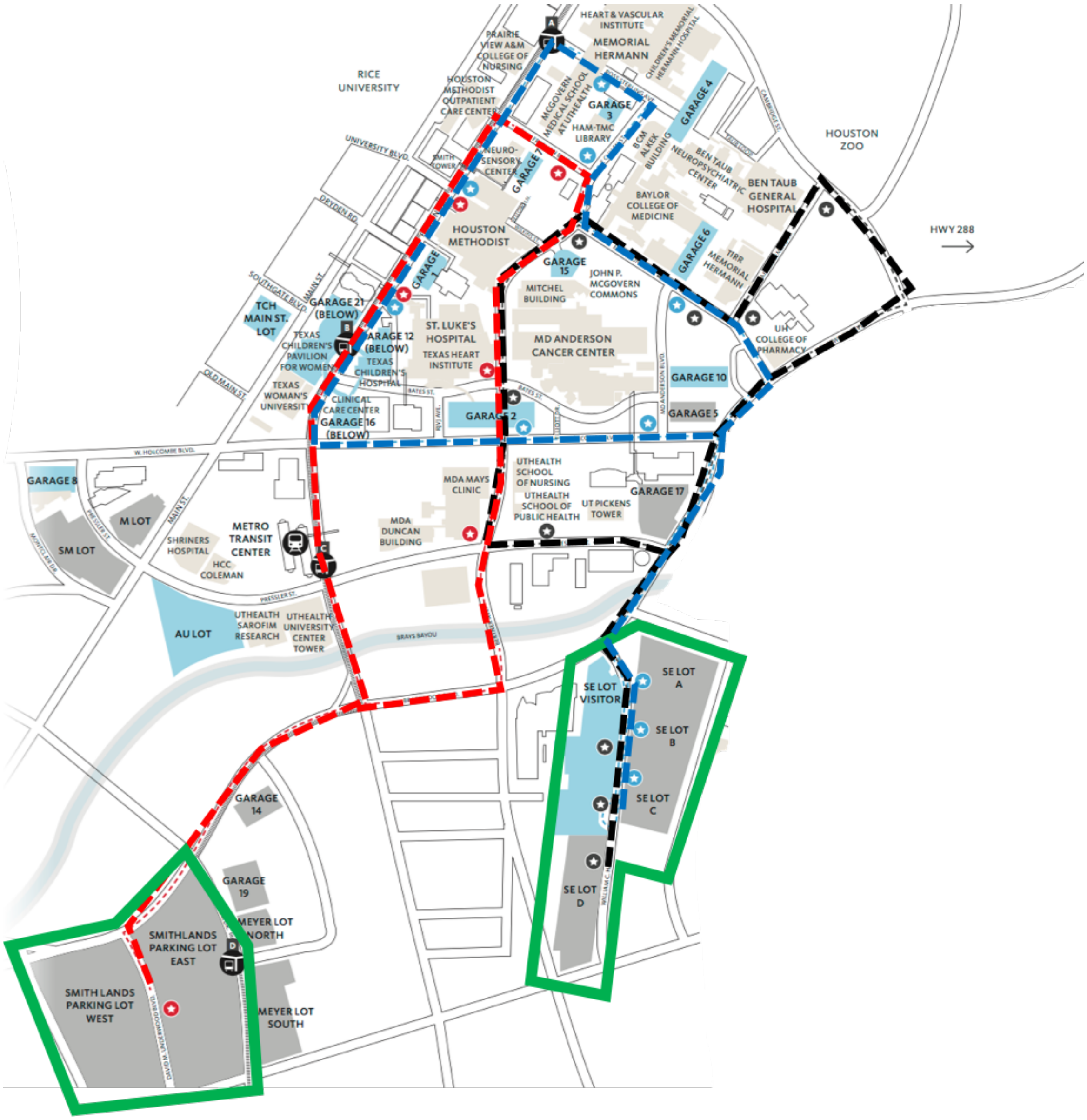

Fig. 2.3 Texas Medical Center Shuttle Routes [57]

The shuttles provide a comprehensive system capable of transporting employees to many locations within the medical center, but are neither frequent nor quick. The peak frequency, journey time, number of stops, fare price, and modal share (the percentage of travelers using a certain transit option) for each route are presented in Table 2.2. Because some of the shuttle stops for different routes overlap, there exist 12 distinct stops [57].

Table 2.2 Shuttle System Peak Frequency, Journey Time, Number of Stops, Fare Price, and Modal Share [63] [57] [61]

Vehicle	Frequency	Journey Time	Stops	Fare	Modal Share
Red Shuttle	AM: 5-6 mins PM: 8 mins	13 mins	5	Free	11%
White Shuttle	AM: 5-10 mins PM: 10 mins	8 mins	6	Free	18%
Blue Shuttle	10 mins	9 mins	7	Free	4%

2.3.2 Light Rail

Of the employees that park at the Smith Lands or South Extension lots, 41% take light rail, pictured in Figure 2.4. [64].

Fig. 2.4 Texas Medical Center Light Rail [7]

Light rail costs $1.25 per ride [65]. The average weekday light rail ridership is 3,000 rides [64]. The light rail line connects the Smith Lands lot to three locations within TMC [60]. The light rail routes are shown in Figure 2.5.

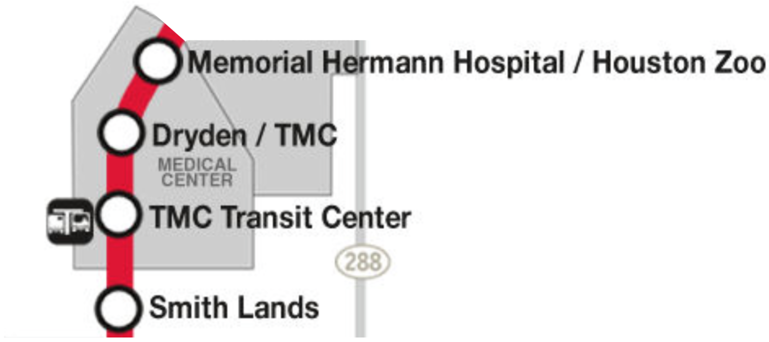

Fig. 2.5 Texas Medical Center Light Rail Route [60]

The light rail system is quicker and more frequent than the shuttle system, but services only 3 stops compared to the 12 that the shuttles service [60] [57]. In addition, the light rail only stops at one of the parking lots, while the shuttles stop at both. Table 2.3 summarizes the light rail peak frequency, journey time, number of stops, fare price, and modal share.

Table 2.3 Light Rail Peak Frequency, Journey Time, Number of Stops, Fare Price, and Modal Share [60] [64]

Vehicle	Frequency	Journey Time	Stops	Fare	Modal Share
Light Rail	Every 6 minutes	8 minutes	3	$1.25	41%

The Medical Center encourages its employees to arrive at the parking lot 30 minutes prior to their clock in time in order to arrive at work on time, meaning that the last mile adds half an hour to an employee's commute [66].

2.4 Performance and Service Level Targets

In light of the current service provision (which sets the standard to beat), the performance and service level targets for the future system should be set. The autonomous system should aim to be comprehensive (like the shuttle system), fast (so as not to add half an hour to an employee's commute), and frequent (like the light rail system).

2.4.1 Capacity

TMC quotes the morning peak period as running 3 hours from 6 AM to 9 AM, corresponding to when the shuttles operate most frequently [57]. It was assumed that all 8,000 employees parking in the Smith Lands and SE lots require transport during the three-hour peak. The average people per hour (pph) in the peak was determined using the length of the peak.

$$Average\ peak\ pph = \frac{Total\ riders}{Number\ of\ hours\ in\ peak}$$

Within the peak, an hour occurs in which the number of employees needing transport is highest. Transport engineers have dubbed this the design hour, defined as the "hour with traffic volume that represents a location specific peak hour value" [67]. It was assumed that the design hour pph is 1.5x the average peak pph. Table 2.4 summarizes the total peak ridership, average peak pph, and design hour pph.

$$Design\ hour\ pph = 1.5 \times Average\ peak\ pph$$

Table 2.4 Total Peak Ridership, Average Peak Rishership per Hour, and Design Hour Ridership

	Total Peak Ridership	Average Peak pph	Design Hour pph
Smith Lands	4,500	1,500	2,250
South Extension	3,500	1,167	1,750

The design hour get its name because it dictates the design of the system such that the system is designed to accommodate the design hour pph [67]. Thus, the design hour volume was used to calculate the number of vehicles required.

2.4.2 Journey Time

Using the chosen route, the round-trip journey time was calculated. The distance and travel time between each stop was determined. It was assumed that, between each stop, the pods accelerated at 1 m/s^2, travelled at an average speed, then decelerated at 1 m/s^2. The pods were then assumed to idle at each stop for 30 seconds to allow passengers to load and unload before repeating the process. This process was repeated for three different design pod speeds: 10 mph, 20 mph, and 30 mph. The average speed was assumed to be lower than the pod design speed to take stopping and turning into account. The assumed average speed for each design pod speed is shown in Table 2.5.

Table 2.5 Design Speed and Average Speed

Design Speed	Average Speed
10 mph	5 mph
20 mph	15 mph
30 mph	20 mph

The time to travel between each stop for the red, white, and blue routes for 10 mph, 20 mph, and 30 mph pods are shown in the Appendix in Tables A.1, A.2, and A.3. The total round trip journey time, including stops, acceleration, and deceleration, for each vehicle speed for the different routes is presented in Figure 2.6 and in the Appendix in Table A.4.

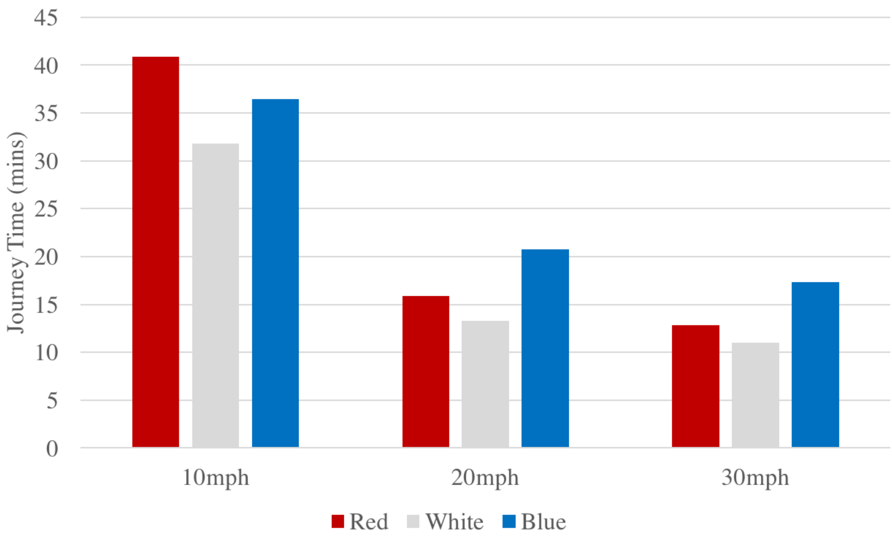

Fig. 2.6 Round Trip Journey Time (Including Acceleration, Deceleration, and Stops) Comparison by Pod Speed and Route

The 30 mph pods were chosen to be the most advantageous because the journey times are the fastest, fewer pods would be needed, and 30 mph is the speed limit within urban areas of Houston [68]. The single end-to-end journey in-vehicle time comparison for the pods, shuttles, and light rail is shown in Figure 2.7.

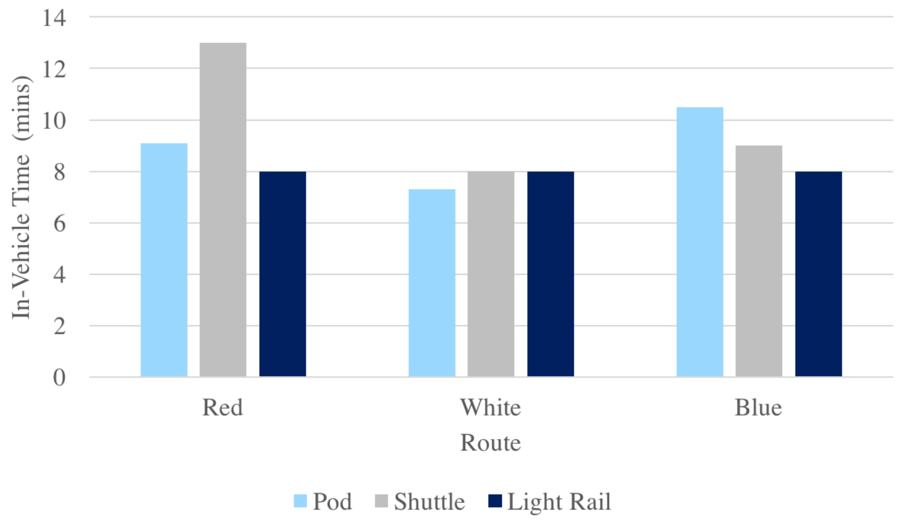

Fig. 2.7 Single End-to-end Journey In-Vehicle Time Comparison by Mode and Route [60] [57] [59]

The light rail has the shortest in-vehicle time. The in-vehicle time for the blue route is longer for the pods than the shuttles because of the stop time. The current shuttle system stops when requested and for however long is necessary at each stop [63]. The pod system was assumed to stop for 30 seconds at each stop. The blue route incorporates the most stops (7), stopping for 3.5 minutes total [57]. Rather than stopping for a set time at each stop, the pod system could be responsive to demand like the current shuttles, thus shortening the in-vehicle time.

Assuming an average walking speed of 5 ft/s, the maximum time required for the first and last elements of the journey (i.e. the walk to the pick-up point and the walk from the drop-off point to the intended destination) was calculated. The maximum time spent walking for each of the modes is displayed in Figure 2.8.

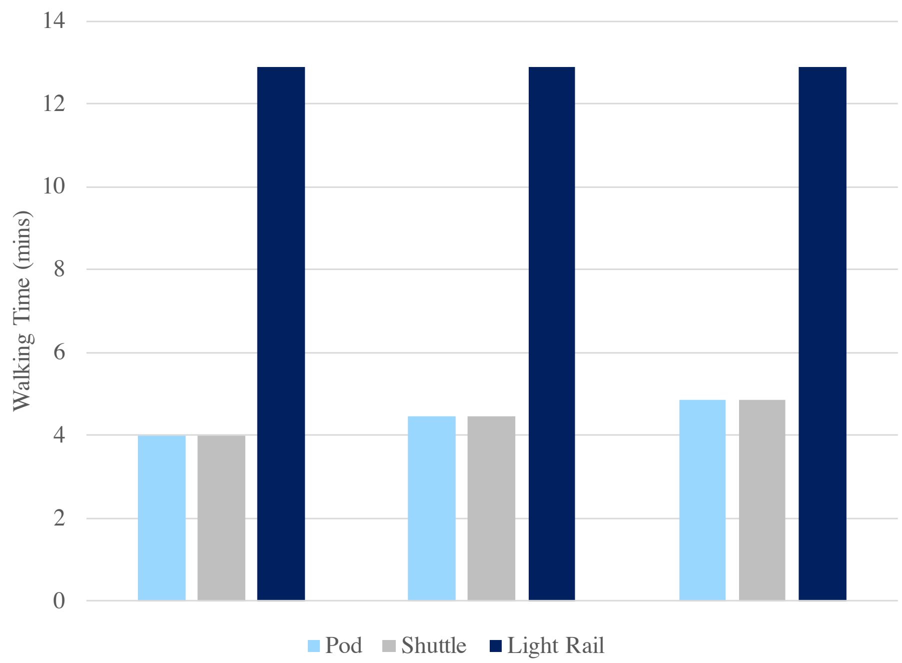

Fig. 2.8 Maximum Single Journey Walking Time Comparison by Mode and Route [59]

The combined in-vehicle and walking time for a single journey are shown in Figure 2.6.

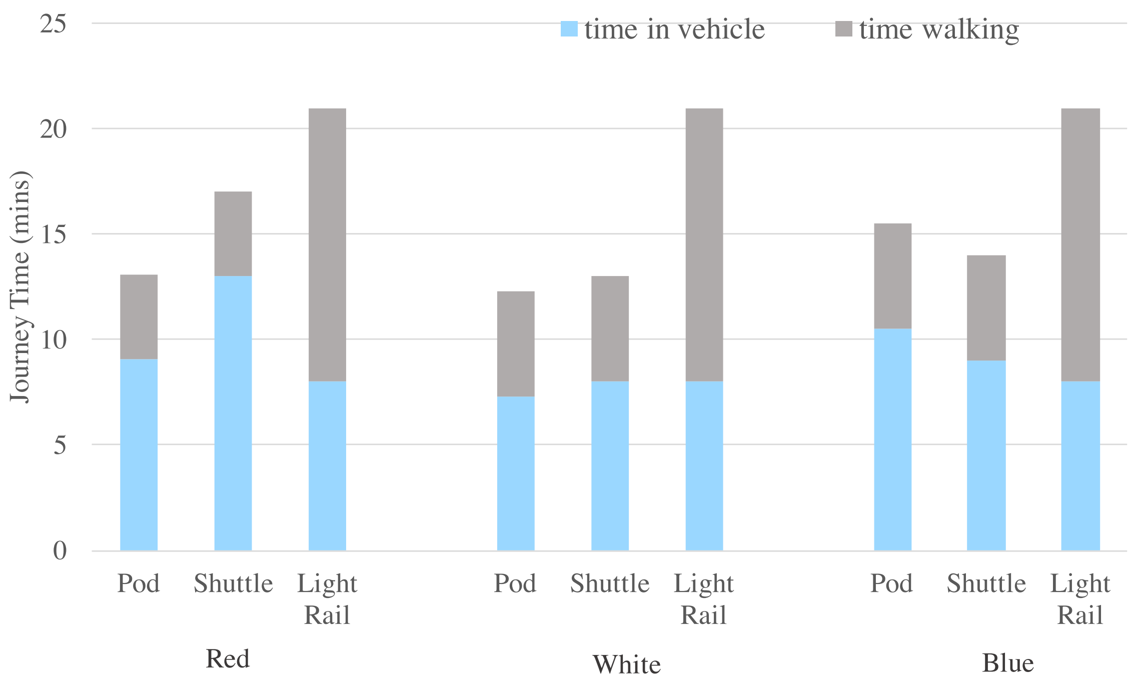

Fig. 2.9 Single Journey Time Including End-to-End In-Vehicle Time and Maximum Walking Time Comparison by Mode and Route [60] [63] [59]

Because there are fewer light rail stops, commuters using the light rail would have to walk farther to reach their intended destination, thus increasing their total journey time. Though the light rail has the shortest in-vehicle travel time, the total journey time including walking and in-vehicle time is longer than that of the shuttles and pods.

2.4.3 Frequency

During the design hour, 113 pods must depart the Smith Lands lot and 88 pods must depart the SE lot, amounting to 201 total pod departures. This is equivalent to one pod departure every 18 seconds. The frequency of the pod departures for each lot is shown in table Table 2.6.

Table 2.6 Pod Departures, Frequency

	Pod Departures	Frequency (seconds)
Smith Lands	113	32
South Extension	88	42
Total	201	18

The Smith Lands lot only incorporates the red route. For this, the red line should be capable of accommodating everyone who parks in the Smith Lands lot, thus requiring pod departure every 32 seconds. Both the white and blue lines pick up employees from the SE Lot. From ridership data, there are 4.5x more riders on the white line than the blue line [61]. This means that there are 320 blue riders and 1,400 white riders during the design hour. This requires a maximum of 16 blue pods and 72 white pods departing per hour. The pod departure frequencies for the red, white, and blue lines are shown in Table 2.7.

Table 2.7 Design Hour pph, Design Hour Volume, and Design Hour Frequency

	Design Hour pph	DHV	Design Hour Frequency (seconds)
Red	2,250	113	32
White	1,400	72	50
Blue	320	16	225

The frequency of the pods is compared to that of the current transportation options in Figure 2.10 and in the Appendix in Table A.5. The pods have an advantage over the shuttle and light rail systems because they would operate more frequently, thus providing a quicker and more convenient service.

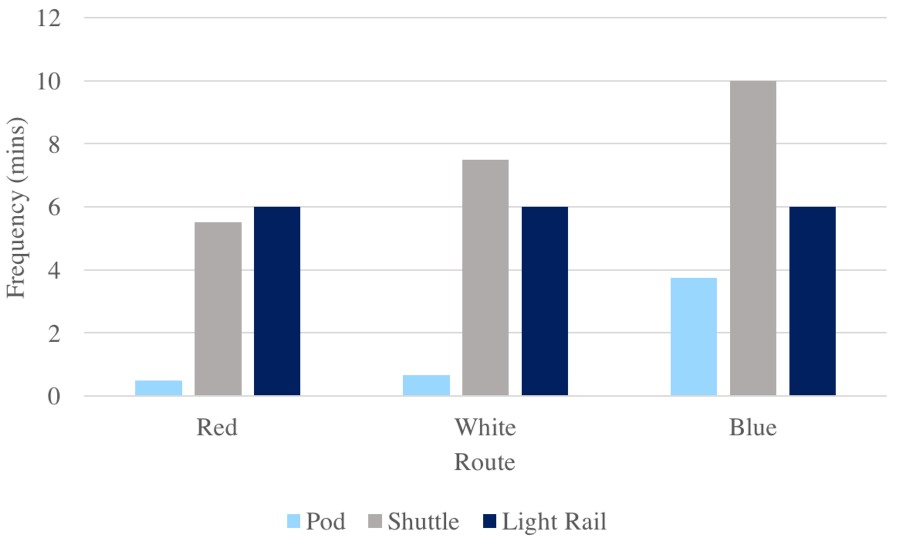

Fig. 2.10 TMC Design Hour Frequency by Mode and Route [57] [60]

The maximum single-leg journey time of the pods compared to the bus and the rail, including the walk to the pick-up station, the wait for the vehicle, the ride to the drop-off station, and the walk to the destination for each mode and each route is illustrated in Figure 2.11 and in the appendix in Table A.6.

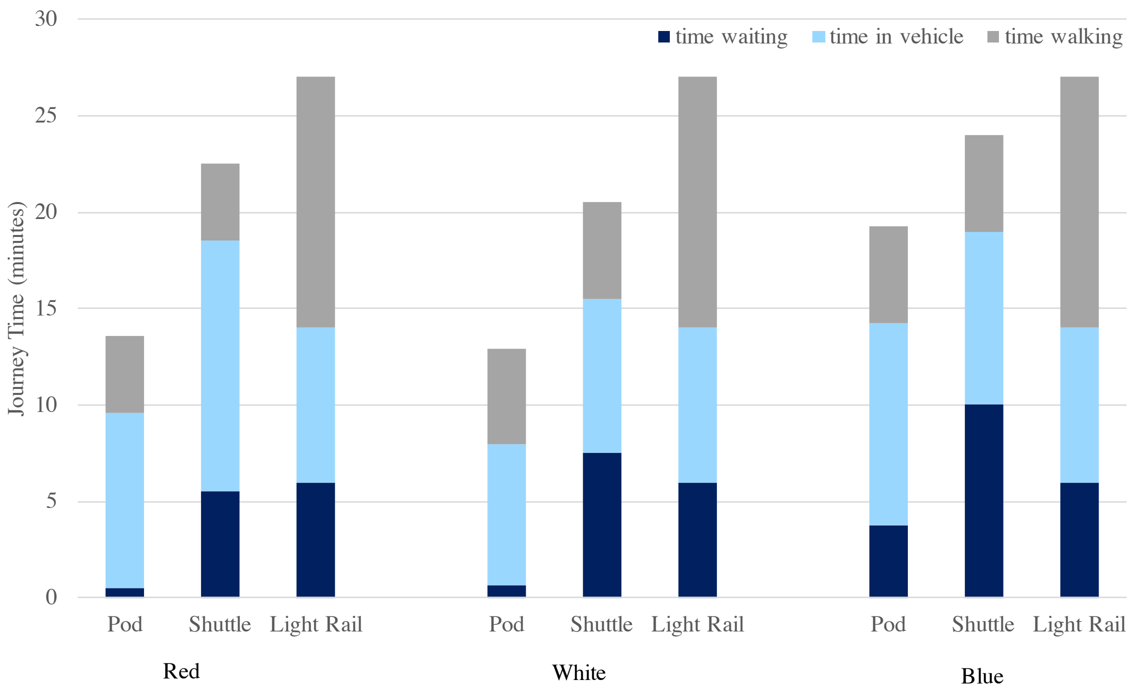

Fig. 2.11 Single Journey Time Including Maximum Wait, End-to-End In-Vehicle Time, and Maximum Walking Time Comparison by Mode and Route [57] [60] [63]

The pods have the shortest single journey time because commuters using the AV system do not need to walk as far as those using the light rail and do not need to wait as long as those using the shuttles.

2.5 Routes and Infrastructure

2.5.1 Routes

It was assumed that the current shuttle routes were carefully chosen by the Medical Center to provide a comprehensive service for employees, transporting them to the most desired locations within the medical center. For this, the autonomous system route was chosen to be a replica of the current shuttle routes. This provides an advantage for the analysis because the shuttle system can act as a benchmark to compare to the proposed system. The red, white, and blue routes are illustrated in Figure 2.3. The autonomous system could be further improved by optimizing the routes.

2.5.2 Infrastructure

The AV system infrastructure would consist of stations and segregated pathways. The stations would be located in the Smith Lands and SE lots. The fixed route would begin and end at the stations. When not in use, the autonomous pods would be stored and charged in the stations. The pods would run along segregated routes on the current roads within TMC to make them safer, faster, and adopted quicker.

Smith Lands

The Smith Lands lot would contain a station for red route pods. It was assumed that the load time (the time for passengers to fill into the pod) could last longer than 32 seconds (the headway of the red route). For this, two lanes of pods would be needed within the station. The frequency of pod departures in each lane would be 1 minute and 4 seconds, providing adequate time for passenger loading between departures.

Different locations for the pod stations were considered. The best idea was to have two stations that could be easily connected to the road, located to minimize car-pod interactions. The location is illustrated in Figure 2.12 where each red box indicates one station.

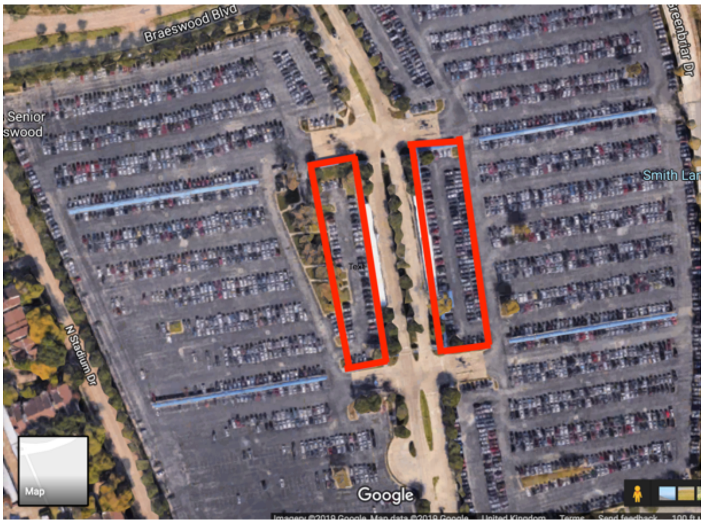

Fig. 2.12 Two Pod Station Locations in the Smith Lands Lot [59]

Pods would not cross cars within the parking lot because they would have their own dedicated space with road access. This location would take advantage of current infrastructure; the shuttles currently stop at these locations so they already have covered waiting areas and restrooms. The only concern is that the pods would be using the same entrance and exit as the cars, which could be disruptive. The farthest parking spot would be 600 feet from the pod station [59]. Assuming an average walking speed of 5 ft/s, every parker would be within 2 minutes of the station.

Different ideas were analyzed, including the idea of viaducts to avoid car-pod interactions and ground-level stations. It was determined that ground-level stations offer the most economic option. For this, some parking spots would need to be paved over, eliminating 3% (150) of the total parking spots in the Smith Lands lot [59]. The Medical Center owns the parking lot and its employees pay for contract parking [62]. For this, TMC would lose money on the lost parking spots each month. This loss will be taken into account in the economics portion described in Section 2.7.

Next, the size and layout of the pod stations were designed. As described in Section 2.6.2, 42 pods would service the Smith Lands parking lot, 21 at each station. During the 6 peak hours (3 in the morning and 3 in the afternoon), all the pods would run. At any given time, 58% of the pods would be out on the route while 42% of the pods would charge. This means that 9 pods would be charging at either station at any given time during the design hour. For this, 9 charging bays would be needed in the station. The station can be imagined as 2 lanes for charging with an extra row for pods entering or departing the station. This requires three lanes per station. The pod charging bays would be twice as long and twice as wide as the pods to accommodate pod movements and a charger. The middle lane would also be twice as wide as the pods. A 20-passenger pod was assumed to have the following dimensions:

Length: 5.5 meters Width: 2.1 meters Height: 2.5 meters

For this, the lanes would each be 4.2 meters wide and the charging stations would each be 11 meters long. Therefore, the station would be configured as in Figure 2.13, with 9 charging stations and 9 free spots.

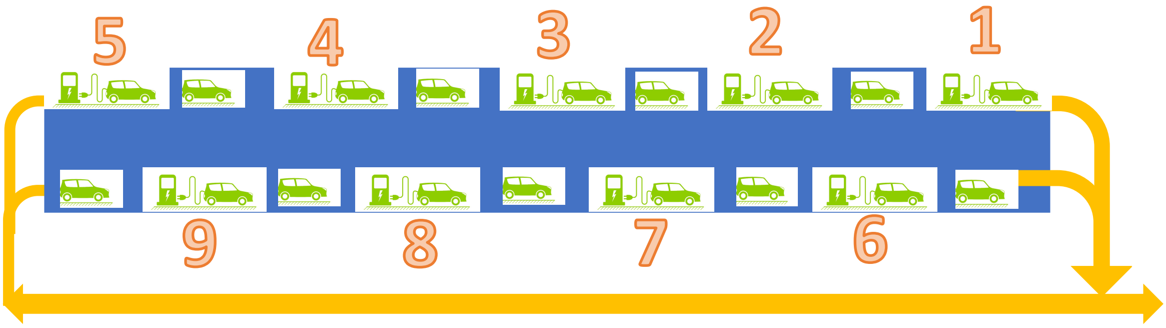

Fig. 2.13 Visualization of Pod Station Layout for Smith Lands Lot

The station would have the following dimensions, which fit within the red rectangle in Figure 2.12 [59]:

Length: 99 meters Width: 12.6 meters

The station would be unable to store all the pods at once (i.e. when all the pods are out of use on the weekends or in the early morning hours). During these out-of-service hours, the parking lots were assumed to be nearly empty because employees would not be at work. Therefore, the pods could loiter in the parking lot.

South Extension Lot

The SE Lot services the white and blue routes. The white pods would depart every 50 seconds while the blue pods would depart every 225 seconds. Combined, this would be one pod departure every 41 seconds. The layout would include two lanes with a departure every 82 seconds from each of the lanes. The white and blue routes would share the two lanes, but the pods should be marked or colored to make clear to riders which pod to board.

The locations for the pod stations, illustrated in Figure 2.14, were chosen to minimize pod-to-car interactions, grant access to the roads, and eliminate the need to pave over parking spots. Though the chosen location saves money by not replacing parking spots, it needs infrastructure. The farthest parking spot would be 800 feet away, so each parker would be 2 mins and 40 seconds from the station [59].

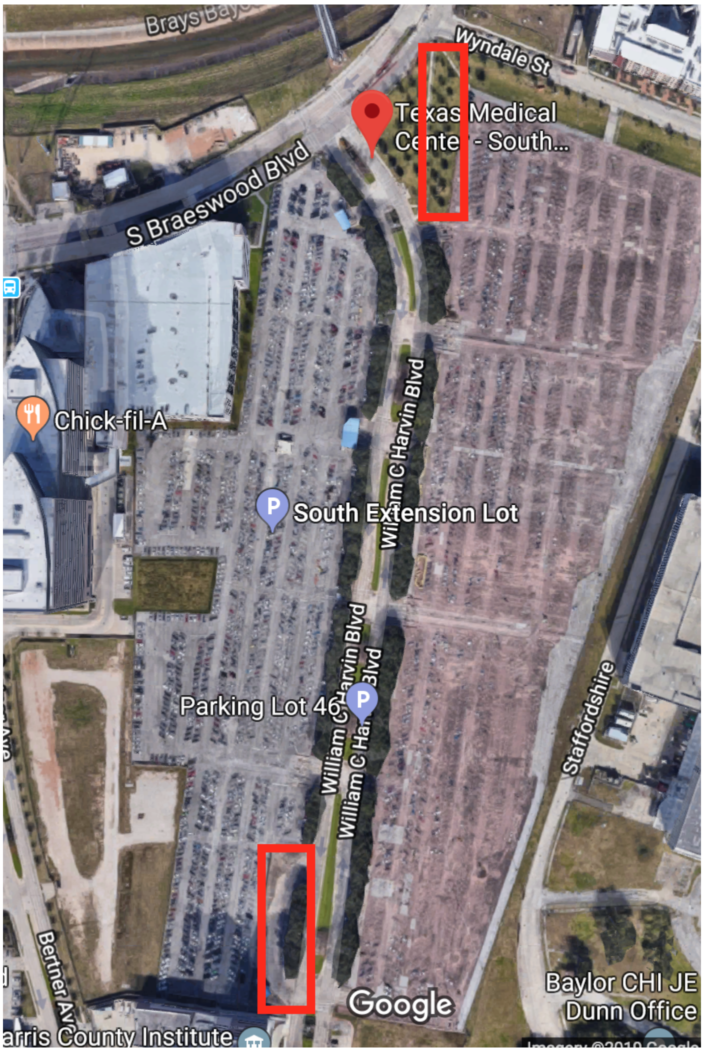

Fig. 2.14 Two Pod Station Locations in the South Extension Lot [59]

As described in Section 2.6.2, there would be 31 pods that service the SE lot. This means that 15-16 pods would use each station with 8 charging bays. At any time during the design hour, fewer than 8 pods would be charging in the station. Outside of the hours of operation, all 15-16 pods could be stored in the station, as shown in Figure 2.15.

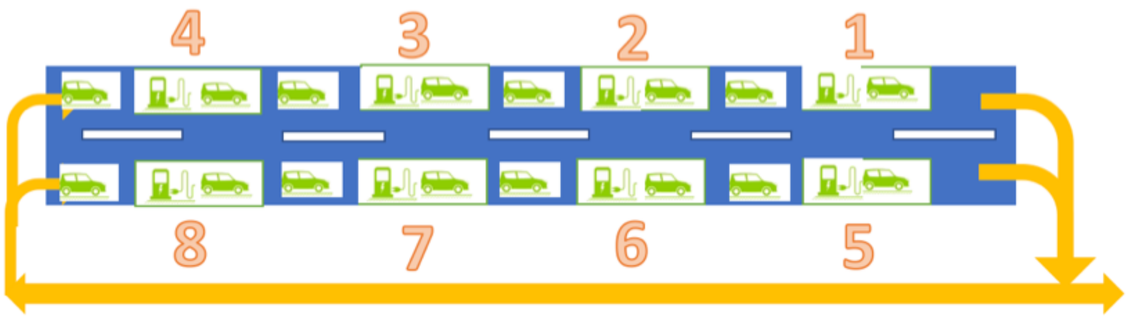

Fig. 2.15 Visualization of Pod Station Layout for South Extension Lot Outside of Operational Hours

For the station to be able to store two lanes of 8 pods each with an empty middle lane, it should have the following dimensions, which fit within the rectangles shown Figure 2.14 [59].

Length: 88 meters   Width: 12.6 meters

Possible Collisions

A scheduling model in excel was used to investigate possible collisions within the pod stations and at different stops along the route in order to minimize vehicle-to-vehicle interactions. This was done by working out the location of each pod step by step, each time a pod enters or leaves the station. This model found that the shortest amount of time between pod movements within the pod stations was 12 seconds, plenty of time for the pods to safely maneuver the station without colliding with another pod. This means that potential collisions would be mitigated by the long time intervals between pod movements.

On the route, at a stop in which the white and red lines (the most frequent lines) both stop (Bertner @ Bates), the amount of time between vehicle movements would be 35 seconds, which would provide plenty of time for the pods to move safely without collisions. In addition, AVs should gain the capability to negotiate with each other in order to safely transport passengers while interacting with other AVs and eventually other human-operated vehicles.

2.6 Vehicle Fleet

2.6.1 Vehicle Size

The goal of this analysis was to replicate the current shuttle routes with smaller vehicles that operate more frequently. The current TMC red, white, and blue shuttles hold 38, 65, and 38 passengers respectively [69]. For the autonomous system to operate more frequently, smaller vehicles were chosen. Initially, 4-passenger, 10-passenger, and 20-passenger pods were proposed. Because the pods would operate along a small number (3) of fixed routes while transporting many people per hour, medium-sized, 20-passenger pods were chosen. A 20-passenger pod designed by Ohmio is depicted in Figure 2.16.

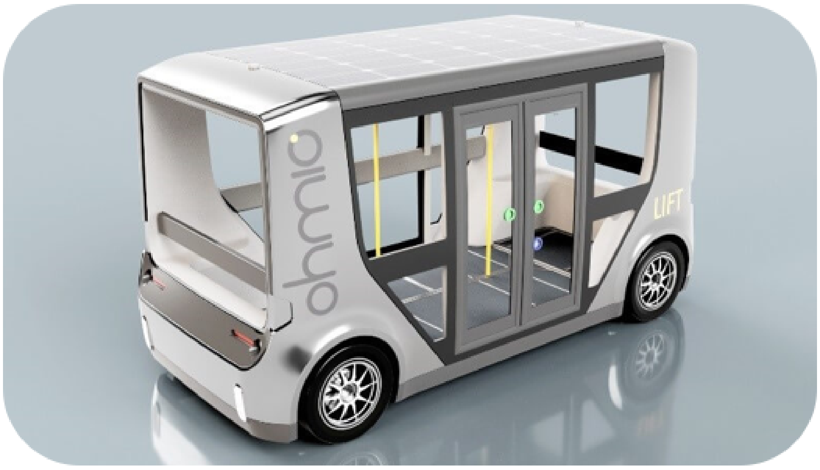

Fig. 2.16 20-passenger Ohmio Autonomous Pod [70]

2.6.2 Number of Vehicles

The number of pod departures needed to transport the design hour number of riders was found by dividing the design hour pph by the capacity of the pods.

$$Number\ of\ design\ hour\ pod\ departures\ needed = \frac{Design\ hour\ pph}{Capacity\ of\ shuttles}$$

Table 2.8 summarizes the design hour pph and the number of pod departures needed during the design hour.

Table 2.8 Design Hour pph and Design Hour Pod Departures Needed

	Design Hour pph	Design Hour Pod Departures Needed
Smith Lands	2,250	113
South Extension	1,750	88
Total	4,000	201

Though 201 total pod departures are needed in the design hour, the fleet size would be less than 201 pods because the pods would make multiple trips per hour. Dividing the number of pod departures required by the number of circuits per hour a pod could run gave the fleet size.

$$Fleet\ size = \frac{Design\ hour\ pod\ departures}{Circuits\ per\ hour}$$

The round-trip journey times for each line was found in Section 2.4.2. This does not include the time that the pods must use for charging between trips. Assuming that the energy requirement of the pods is .5 kWh/km for movement and 10kW for air conditioning with a 25 kWh battery and a maximum rate of charge of 30 kW, the charging times were found to be 9 minutes, 8 minutes, and 13 minutes for red, white, and blue pods respectively. The round trip journey time including charging was used to find out how many circuits per hour the pods are capable of running. Then, the fleet size was determined, summarized in Table 2.9.

Table 2.9 Total Round Trip Journey Time with Charging, Pod Circuits per Hour, Pod Departures per Hour, Pods Needed per Hour

	Round Trip Journey Time	Circuits per Hour	Departures per Hour	Fleet Size
Red	22 mins	3	113	42
White	19 mins	3	72	22
Blue	35 mins	2	16	9

The Smith Lands lot (red route) needs 42 pods while the South Extension lot (white and blue routes) needs 31 pods. This leads to an aggregated fleet size of 73 pods.

2.7 Economics

The component costs of the AV system are the cost of vehicles, infrastructure, fuel consumption, and staff. Each component will subsequently be described.

Vehicles

The aggregated fleet size of 73 pods was found in Section 2.6.2. It was estimated that each pod had an upfront cost of $100,000 paid back over a period of 10 years at a 4% interest rate. The annual cost for vehicles would be $887,000.

Infrastructure

The pod stations would replace 150 parking spots in the Smith Lands lot [59]. The Medical Center owns the parking lot and employees pay $78/month for a spot [62]. For this, TMC would lose $140,400 each year. The South Extension lot stations were designed to avoid taking over parking spots. Despite this, both pod stations incur landscaping costs. The cost of the stations includes the cost of the chargers. In addition, there are costs associated with creating barriers to segregate the pod lanes from regular traffic. The infrastructure costs were estimated at $200,000, paid back over 10 years at an interest rate of 4%. The annual infrastructure costs would be $161,000.

Fuel Consumption

The pod operation hours were determined by mirroring the hours that the current TMC shuttles run. The demand was also scaled with the shuttle demand at certain hours. This way, the total hours per day and therefore kilometers per day that all the pods travel were calculated. The pods were assumed to consume .5 kWh/km of electricity for pod movements. Due to Houston's heat and humidity, the pods were assumed to need 10kW of cooling power, which translates to .31 kWh/km of electricity for air conditioning. This sums to a total of .81 kWh/km of fuel consumption. Multiplying this by the total kilometers driven in a day gave the daily pod electricity consumption, which was then used to find the annual electricity consumption. This energy consumption is a conservative estimate because it assumes that cooling power is needed year round. In reality, air conditioning would not be needed in the colder months, and therefore the annual electricity consumption would be lower than what was calculated. The pods would be used 5 days a week because the shuttles are out of service on the weekends, so it was assumed that the pods would also not be needed during the weekends [57].

$$Annual\ fuel\ consumption = .81kWh/km \times total\ daily\ km \times 5\ days/week \times 52\ weeks/year$$

The cost of electricity used for the transportation sector in Texas varies with time, shown in Figure 2.17.

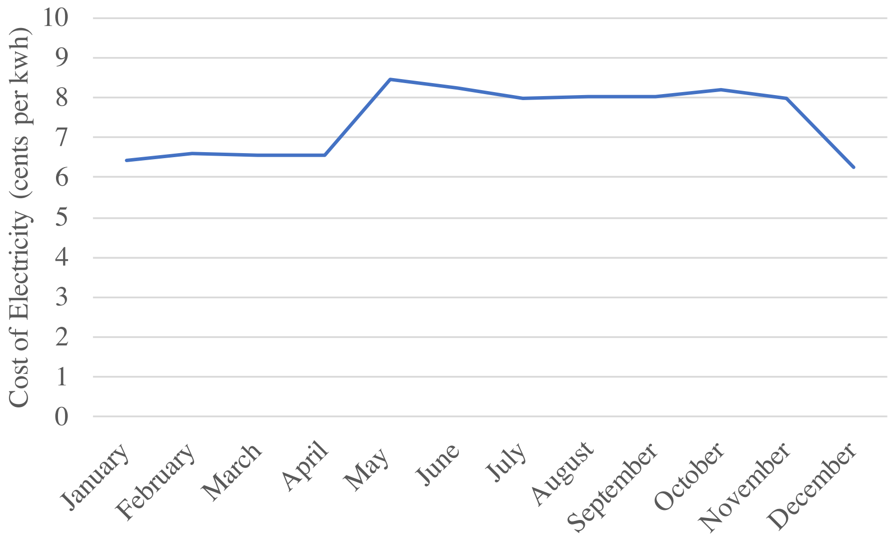

Fig. 2.17 2018 Texas Electricity for the Transportation Sector Price Fluctuations [71]

The average price of electricity for the transportation sector over the past year, 7.44¢/kWh, was taken for the price of fuel [71]. Multiplying this by the annual electricity consumption gave the annual cost of fuel consumption, $342,000.

$$Annual\ cost\ of\ fuel\ consumption = Average\ price\ of\ fuel \times Annual\ fuel\ consumption$$

Staff

A remote operator can monitor and assume control of operation of level 4 AVs from outside the vehicle [28]. It was assumed that remote operators would be necessary to ensure safety and public approval of the proposed AV system. The remote operators were assumed to be responsible for watching 5 pods at a time. The day would consist of three 8-hour shifts in which different numbers of remote operators would be needed depending on how many pods run at a time. It was assumed that a shift manager and secretary would be necessary to manage the remote operators. This safety critical team would require the U.S. average of 151 square feet of office space per person [72]. It was assumed that the office space cost the average price of office space in Houston, $31.34 per square foot [73]. In addition, it was assumed that one mechanic was needed per every 10 pods running. Every employee (remote operators, secretaries, shift managers, and mechanics) were assumed to make $35,000 per year.

There is currently a debate over how many pods a remote operator should be responsible for. For this, the conservative estimate of 1 remote operator for 5 pods was used in the economics model. Over time, as autonomous vehicle technology improves, remote operators could be responsible for watching more pods at a time. This would decrease the cost of staff. The annual cost of staff would be $1,125,000.

2.7.1 Summary of Costs

The summary of the component costs is presented in Table 2.10 and the total annual cost breakdown is depicted in Figure 2.18. The breakeven cost per single ride was found by dividing the total annual costs by the total annual rides assuming a constant level of ridership (75% of employees that park at the Smith Lands or SE lots).

$$Cost\ per\ ride = \frac{Total\ annual\ cost\ of\ system}{Total\ annual\ rides}$$

Table 2.10 Summary of Autonomous System Costs

Cost Description	Cost
Vehicles	$887,000
Infrastructure	$161,000
Fuel Consumption	$342,000
Staff	$1,125,000
Total Annual Costs	$2,516,000
Breakeven Cost Per Ride	$0.84

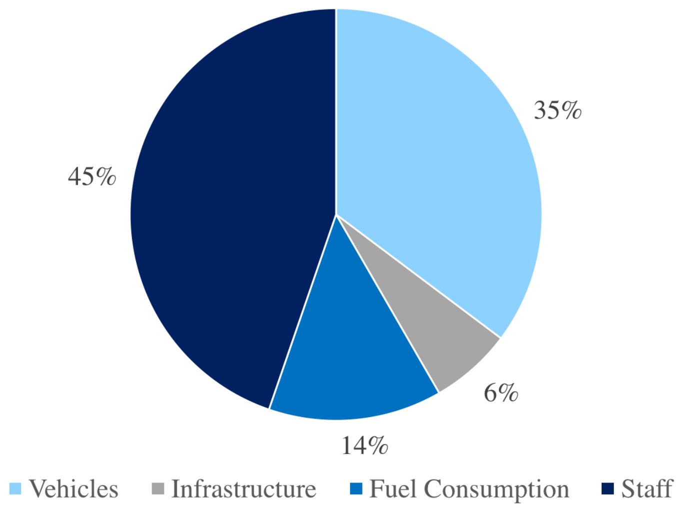

Fig. 2.18 Texas Medical Center AV System Cost Breakdown

2.7.2 Sensitivity Analysis

Many inputs were varied to examine the effect on the overall annual price of the system and the breakeven cost per single ride. The inputs varied were upfront vehicle cost, interest rate, electricity price, and ratio of remote operators to pods. The high, medium, and low estimates for each input are summarized in Table 2.11. Effects of the varied inputs on specific costs components are found in Appendix A.

Table 2.11 Low, Medium, and High Estimates for Sensitivity Study Inputs

Input	Low Estimate	Medium Estimate	High Estimate
Vehicles	\$50,000	\$100,000	\$200,000
Interest Rate	4%	6%	8%
Electricity Price	6.25 ¢/kWh	7.44 ¢/kWh	8.46 ¢/kWh
Remote Operators:Pod Ratio	1:5	1:20	1:50

The effects of the sensitivity study are illustrated in Figure 2.19. The x-axis explains which input was changed, the y-axis depicts the total annual costs of the system in millions of dollars, the stacked bar graph is color-coated to illustrate the component costs of the system, and the breakeven price per single ride is illustrated above each bar. The different variations tested are subsequently described.

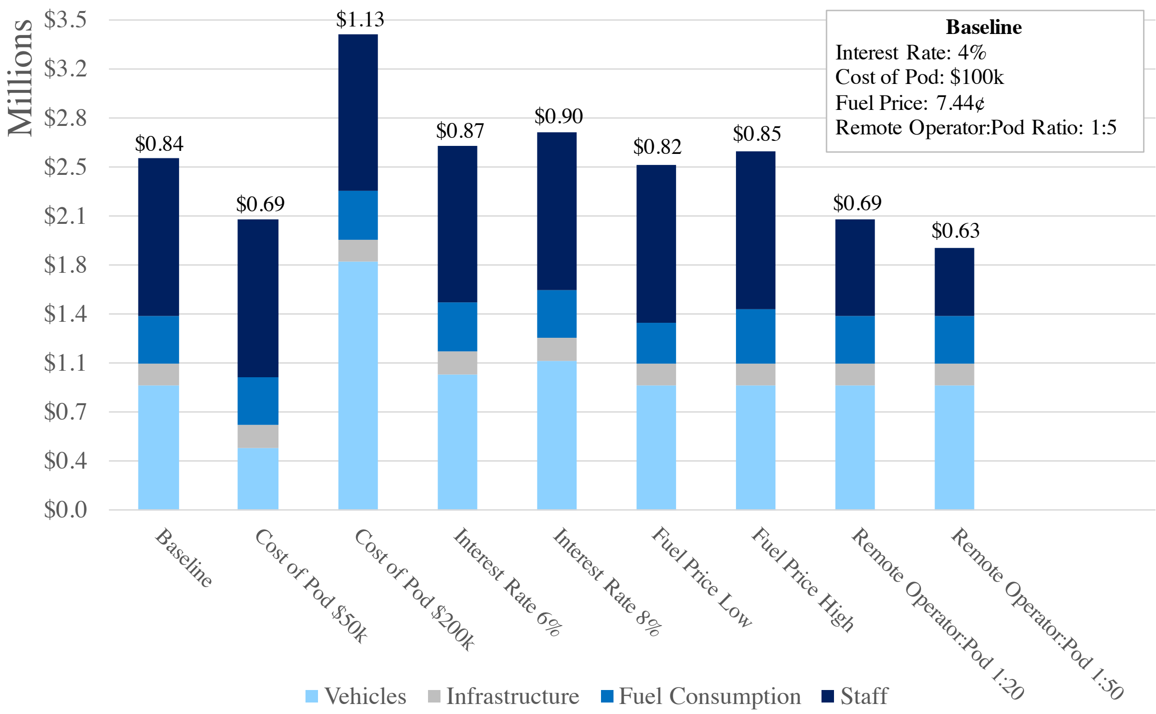

Fig. 2.19 Economics Sensitivity Analysis with Cost Breakdown by Component and Breakeven Cost per Single Ride

The cost of the pods and the remote operator:pod ratio had the biggest effect on the system costs. This is because the fleet size would be large, so a difference in vehicle cost would be compounded over 73 pods. As autonomous vehicle technology improves, remote operators could be responsible for watching more pods at a time, thus decreasing the cost of staff. The cost of the staff decreases rapidly as the remote operator:pod ratio changes from 1:5 to 1:20, but almost levels off between 1:20 and 1:50, shown in Figure 2.20.

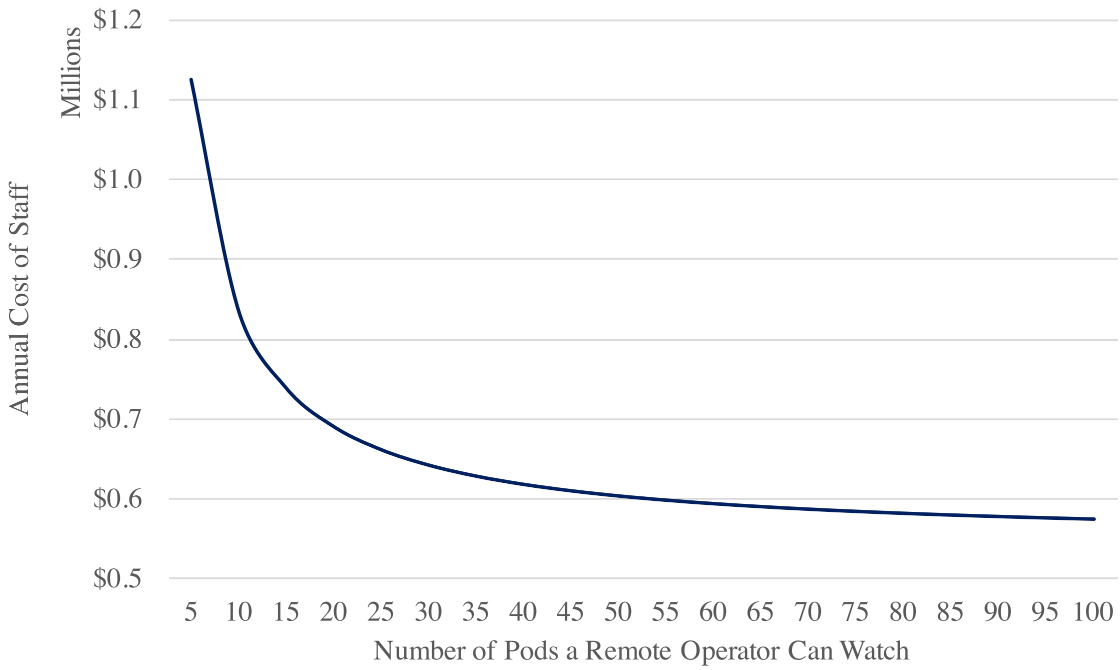

Fig. 2.20 Cost of Staff vs. Number of Pods A Remote Operator Can Watch

The cost of staff levels off because the staff costs of the mechanics, secretary, and shift manager have a larger weight when fewer remote operators are needed. For this, the goal should be to have a remote operator for every 20 pods to decrease the overall costs of the system.

2.7.3 Economics Comparison

Shuttle Economics

The costs of operating the TMC shuttle system were estimated in order to benchmark the AV system costs. The assumptions were: an interest rate of 4% to be consistent with the autonomous system, an upfront cost of the buses of $100,000, annual fuel costs of $1,500 per bus, driver and mechanic salaries of $35,000 for 8-hour shifts, one mechanic to service all the buses, no office space, and no bus station costs because the infrastructure already exists.

Comparison

The cost comparison of the autonomous and shuttle systems is shown in Figure 2.21. The detailed cost comparison is found in the Appendix in Table B.9

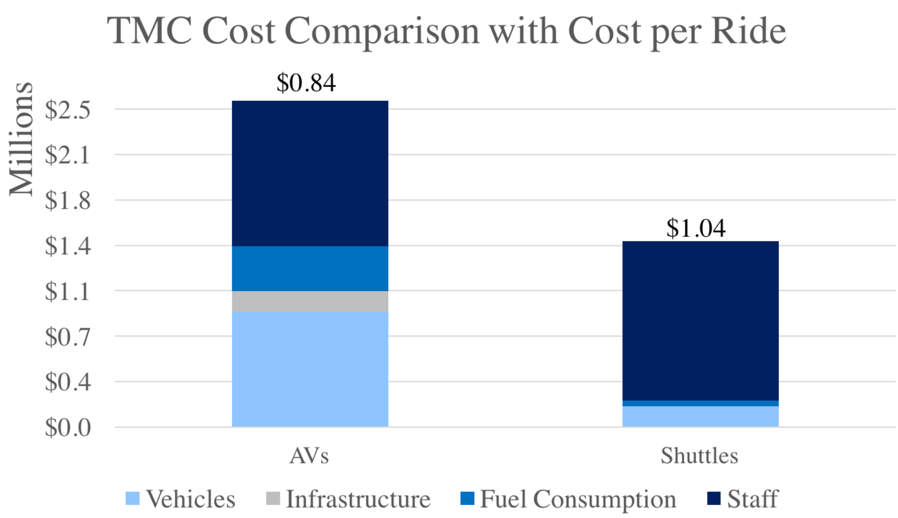

Fig. 2.21 Annual Cost Comparison of Autonomous and Shuttle Systems with Breakeven Cost per Single Ride

The autonomous system would be more expensive than the current shuttle system because it would require far more vehicles (73 pods compared to 13 shuttles), new pod stations to be built, and more fuel consumption to fuel the additional kilometers driven by the larger number of vehicles [63]. The cost of staff for the autonomous system would be less because the vehicles would not require drivers. The breakeven cost per single ride was calculated by dividing the total system costs by the number of annual riders, assuming a constant ridership of 75% of the Smith Lands and SE lot parkers for the AV system and the 33% ridership level of the existing system [61]. Though annual costs of the AV system would be greater, the breakeven cost per single ride would be lower because it was assumed to capture more riders. The autonomous system must exceed 60% ridership levels to yield a cheaper breakeven cost per single ride than the current system, shown in Figure 2.22.

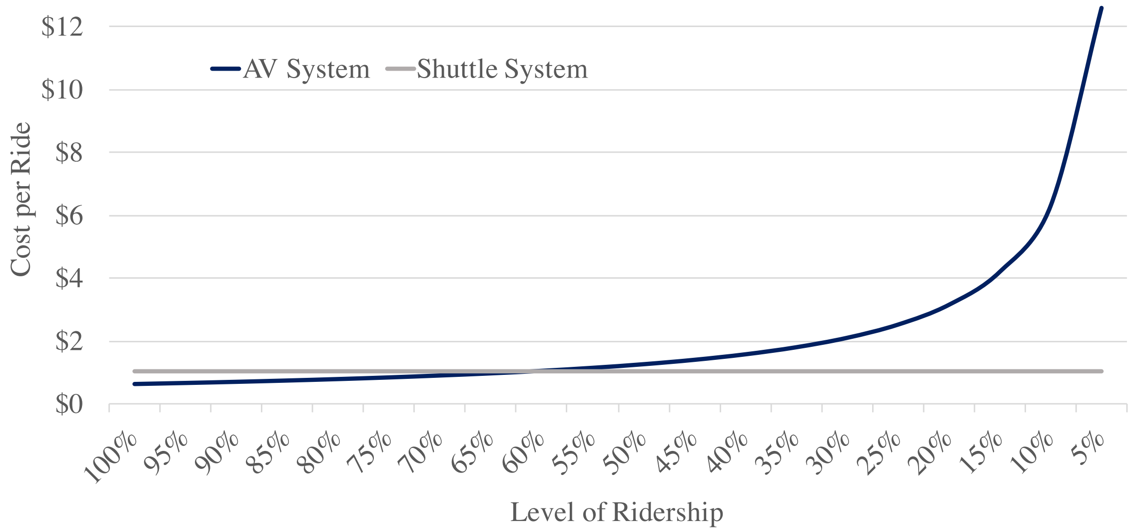

Fig. 2.22 Breakeven Cost Per Single Ride vs. Assumed Ridership Level with Breakeven Cost per Single Ride of Shuttle System

2.7.4 Financial Viability

The financial viability of running the system from the system operator's point of view was calculated. To calculate the profitability, fare price and ridership were assumed. For various fare prices and ridership levels, the payback period and profitability were calculated.

For the base case, a fare price of $1.25 was adopted to reflect the current fare price of light rail [60]. Most pubic transit systems start with lower ridership levels that grow over time. A successful system would attract riders quite quickly and then stabilize at a constant level of ridership. For this, the baseline scenario assumed 50% of final ridership numbers for year 1, 80% for year 2, and 100% for year 3 and onwards. This means it would take 3 years to reach the final ridership level, assumed to be 75%. A period of 10 years was examined because it was assumed that the working life of the AVs would be 10 years. The assumptions are summarized in Table 2.12.

Table 2.12 Assumed Final Ridership Level, Fare, Growth Rate, and Time Period

Final Ridership Level	Fare	Growth Rate	Time Period
75%	$1.25	year 1: 50% final ridership year 2: 80% final ridership year 3+: 100% final ridership	10 years

The costs, revenues, profits, and cumulative profits for each year over a period of 10 years, presented in Table A.12 in the Appendix, were calculated. Figure 2.23 shows the cumulative profits over the 10 year period. This graph presents the initial capital outlay ($7.5 million) as the first point of the graph, the payback period (57 months) as the point where the graph crosses the x-axis, and cumulative profits after the 10 year period ($11 million) as the end point of the graph.

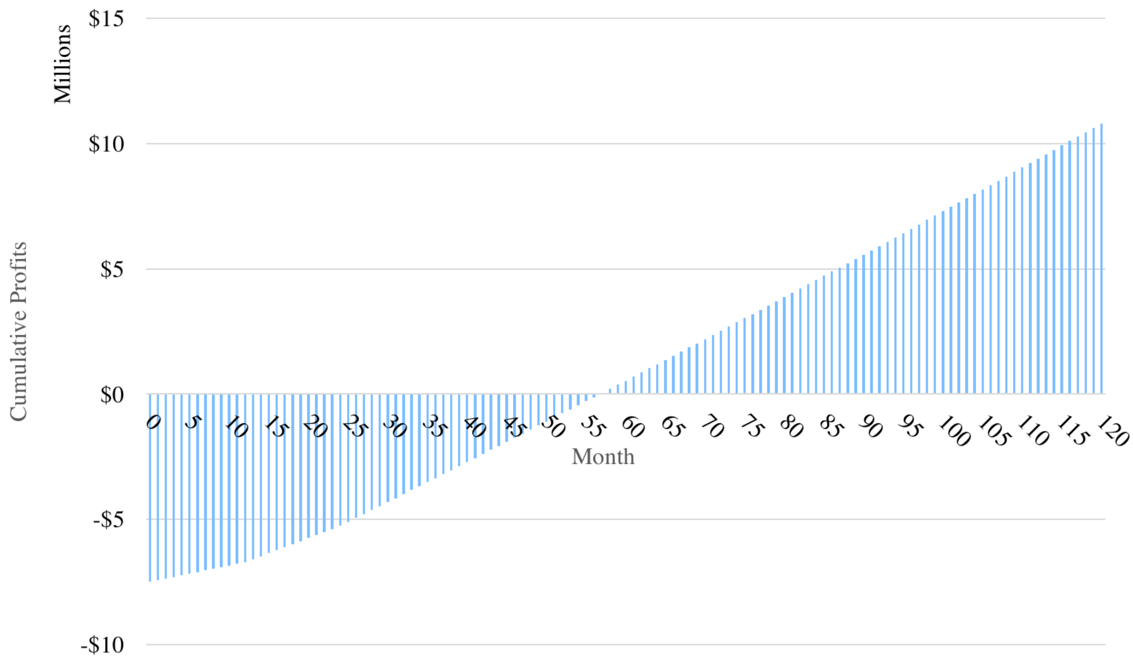

Fig. 2.23 Cumulative Profits of AV System Over 10 Year Period with $1.25 Fare, 75% Final Ridership, and 3 Years to Reach Final Ridership Level

The key variable is the return on capital employed (ROCE), which measures how effectively a company uses its capital to generate profits [74]. It is defined as:

$$ROCE = \frac{Operating\ income}{Capital\ employed}$$

The operating income was found from subtracting the costs from the revenues.

$$Operating\ income = Revenues\ -\ Costs$$

The capital employed is defined as the value of the assets [74]. This dissertation disregards discounting and depreciation, so the capital employed was assumed to be the initial capital outlay that paid for the vehicles and the stations. The ROCE over the 10 year period is presented in Figure 2.24.

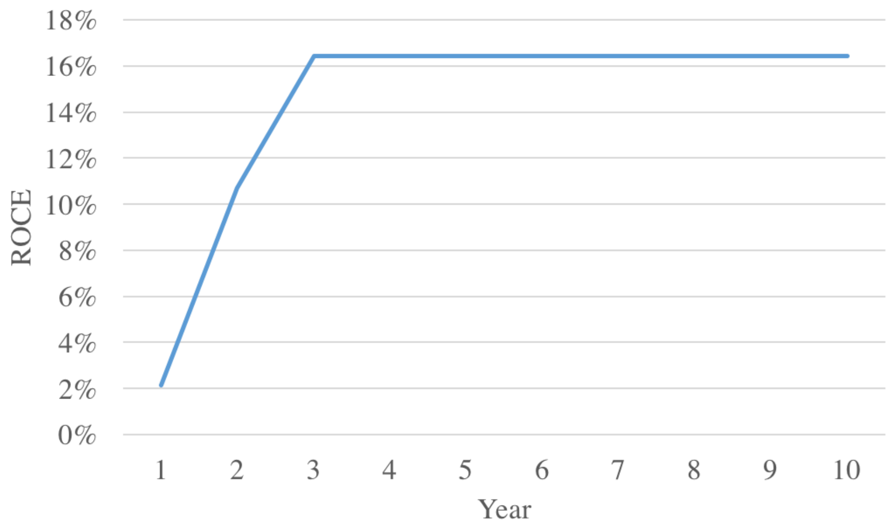

Fig. 2.24 ROCE of AV System Over 10 Year Period with $1.25 Fare, 75% Final Ridership, and 3 Years to Reach Final Ridership Level

The ROCE stabilizes at 16%. A good ROCE should be at least double the interest rate [74]. A 4% interest rate was assumed, so the ROCE is considered good. In addition, the average ROCE value for non-financial corporations in the UK in the past quarter was 12.3% [75]. Therefore, the autonomous system uses capital to generate profits more efficiently than the average UK company.

2.7.5 Sensitivity Analysis

The fare price, ending ridership level, and ridership growth were varied to examine the effect on the payback period and cumulative profits of the system. The effects of the sensitivity study are illustrated in Figures 2.25 and 2.26. The x-axis explains which input was varied while the y-axis presents the payback period in months or cumulative profits in millions of dollars.

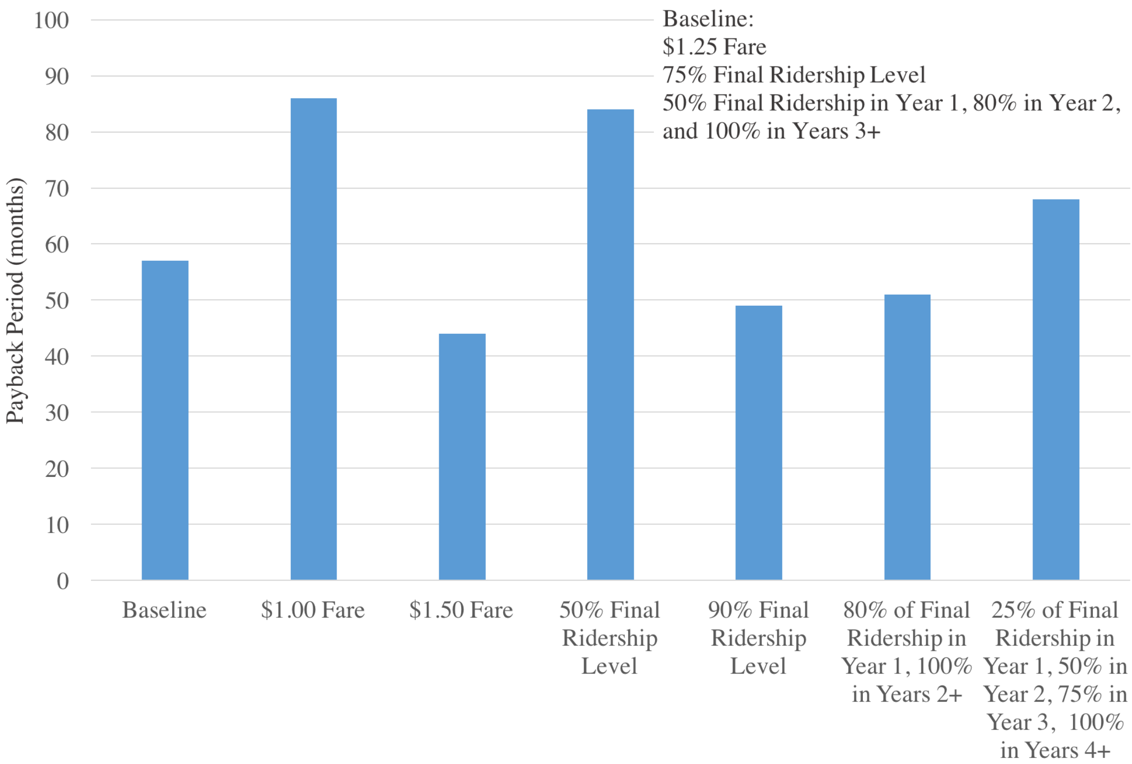

Fig. 2.25 Payback Period Sensitivity Analysis with Baseline, Varied Fare, Varied Final Ridership Level, and Varied Ridership Growth

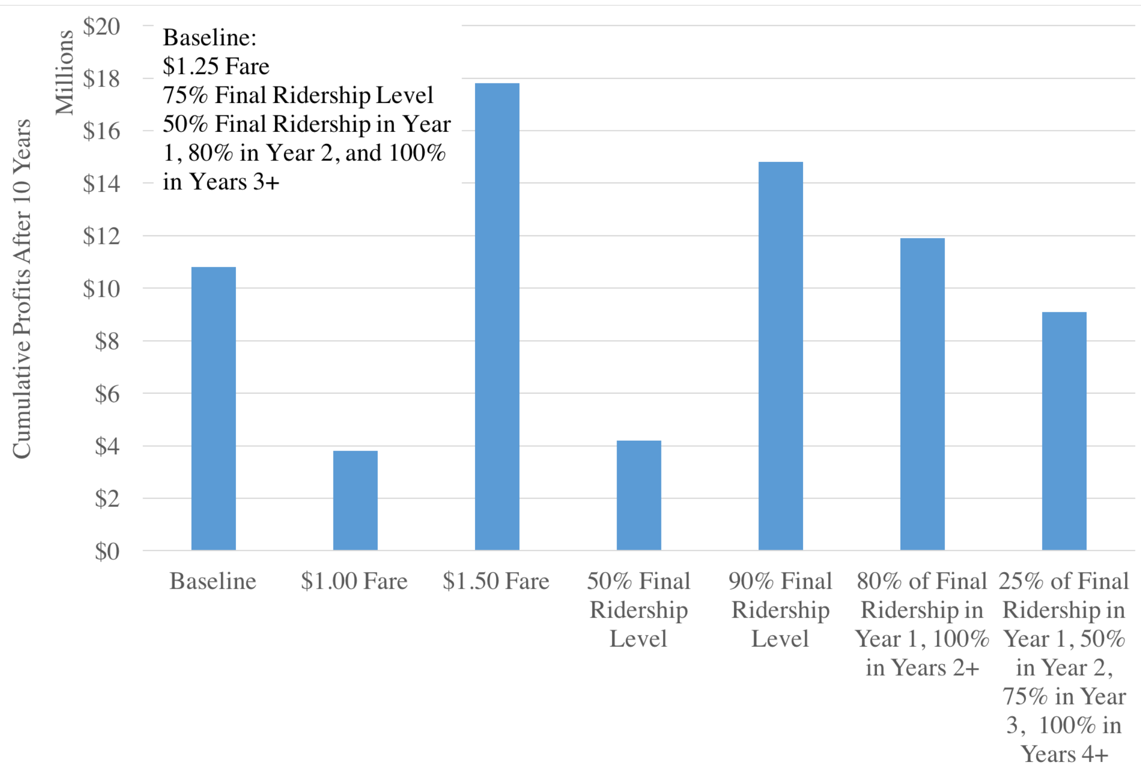

Fig. 2.26 Cumulative Profits After 10 Years Sensitivity Analysis Baseline, Varied Fare, Varied Final Ridership Level, and Varied Ridership Growth

The fare price has the largest effect on the profitability of the system. The different variations tested are subsequently described.

Fare Price

The threshold for the system to be profitable yields a breakeven fare price of $0.87. The system operator would want to earn their money back and make a profit, so the system fare should be higher than the breakeven point. The fare was assumed to be priced the same as the current transit option ($1.25), but it could be priced lower ($1.00) to compete with the existing transit or priced higher ($1.50) to make the system more profitable [60].

Final Ridership Level

The threshold for the system to be profitable is 35% ridership, which is higher than the 33% ridership level of the existing shuttle system [61]. The final ridership level was varied between 50% as the lower bound, 75% as the reasonable baseline, and 90% as the optimistic target for the sensitivity analysis.

Ridership Growth

For the baseline scenario, it was assumed 50% of final ridership numbers for year 1, 80% for year 2, and then 100% for year 3 and onwards. A more optimistic scenario assumed faster uptake in ridership with 80% of final ridership for year 1 and 100% for year 2 onwards. A less optimistic scenario assumes a slower uptake in ridership with 25% of final ridership for year 1, 50% for year 2, 75% for year 3, and 100% for year 4 onwards.

This financial analysis suggests that the TMC system has the potential to be self-financing via farebox revenues over a 10-year loan period if it surpasses a $0.87 fare price or final ridership levels of 35%.

2.7.6 Financing Solution

If the proposed system were to capture less than 35% of the employees that park in the Smith Lands and SE lots as customers, it would be far less attractive for a system operator as it would require a public subsidy or different form of revenue. TMC could charge more for the parking spots to raise additional revenue. If TMC raised the price of the parking spots to cover the difference between the current shuttle system and the autonomous system, each parking spot would need to cost $10 extra each month (13% increase in price) for a total of $88/month. This is realistic because the remote surface lots offer the cheapest parking option [62]. The other TMC surface lots and parking garages range from $105 to $277 per month [62]. Even if the parking spot prices increased to reflect the additional cost of the autonomous pod system, the remote surface lots would still be the cheapest choices for parking.

2.8 Emissions

The Texas electricity generation breakdown by source, presented in Figure 2.27, means that 476 gCO_2e are emitted for every kilowatt hour of electricity generated [76].

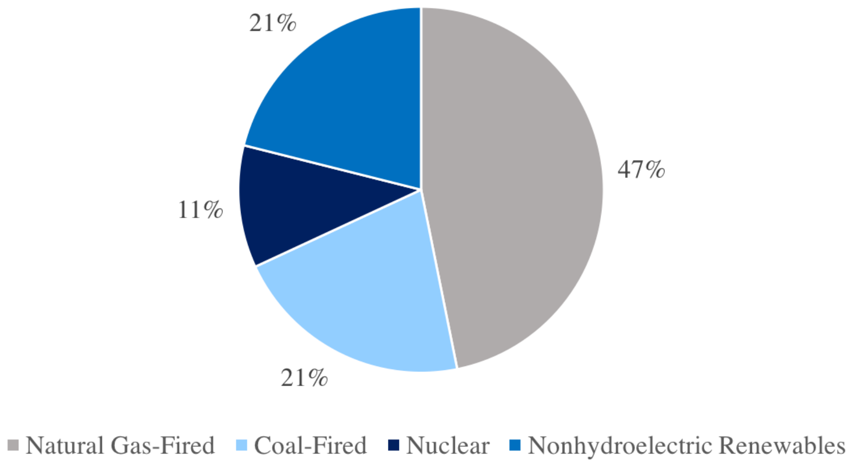

Fig. 2.27 Texas 2019 Electricity Generation by Source [77]

AV System Emissions

The pod energy requirement was assumed to be .81 kWh/km. Assuming the vehicles run at full capacity in the peak, they would emit 19 gCO_2e/passenger km.

Light Rail Emissions

The light rail system emits 4,692 gCO_2e/vehicle km [78] [79]. The vehicle fits 150 standing customers in crowded peak conditions, thus emitting 31 gCO_2e/passenger km during peak conditions [69].

Shuttle System Emissions

An average diesel articulated bus emits 1,323 gCO_2e/ vehicle km [80]. The TMC shuttles run at 135% capacity during peak hours with an average of 67 customers, meaning that the emissions during the peak are 21 gCO_2e/passenger km [63].

Emissions Comparison

During peak conditions, the AV system would have the lowest emissions. In addition, the AV system would use smaller, demand-responsive rather than large, fixed timetable vehicles like the current transport options. For this, the vehicles would have higher average load factors than the current systems. The TMC shuttles and light rail run at 45% of their seated capacity on average [81] [69] [80]. Because the vehicles run at lower occupancy, the average emissions per passenger kilometer are higher than the emissions during the peak. It was assumed that the AV system would run at 75% capacity on average. The peak and average emissions comparisons are illustrated in Figure 2.28 and presented in Table A.13.

As the Texas energy supply relies more upon renewable sources and less on fossil fuels, the emissions per kilowatt hour of electricity produced will decrease. Vermont is the U.S. state with the lowest emissions per kWh of electricity produced (26 gCO_2e/kWh) because it relies heavily upon biomass, hydroelectric power, and other renewables [76] [77]. If Texas could reach the emissions per kWh that Vermont currently boasts, the emissions for the AV system would sharply decrease to 1gCO_2e/passenger km when running at full capacity. The emissions comparison of the three systems at peak and average capacity for the Texas and Vermont energy breakdowns is presented in Figure 2.28.

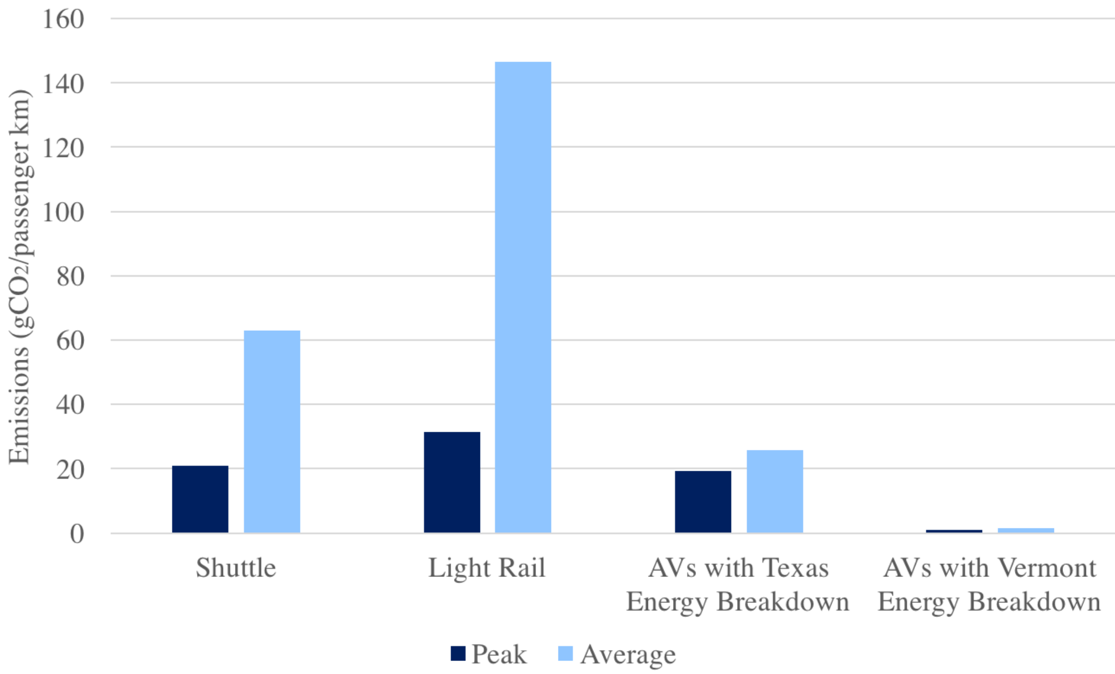

Fig. 2.28 Peak and Average Emissions Comparison by Mode

The emissions comparison suggests that the implementation of the AV system would decrease transport emissions in the Texas Medical Center. In addition, an effective public transit system could encourage TMC employees to choose public transit over personal vehicles for their entire journey to work, further decreasing transport emissions.

Chapter 3

Last Mile: Downtown

3.1 Downtown Overview

Downtown Houston is the largest business district in the region, hosting approximately 150,000 employees in 1.84 square miles [11] [82]. Those employees are distributed among 50 million square feet of office space for over 3,000 businesses, including 8 Fortune 500 companies [11] [82]. The location of Downtown on a map of Houston is shown in Figure 3.1.

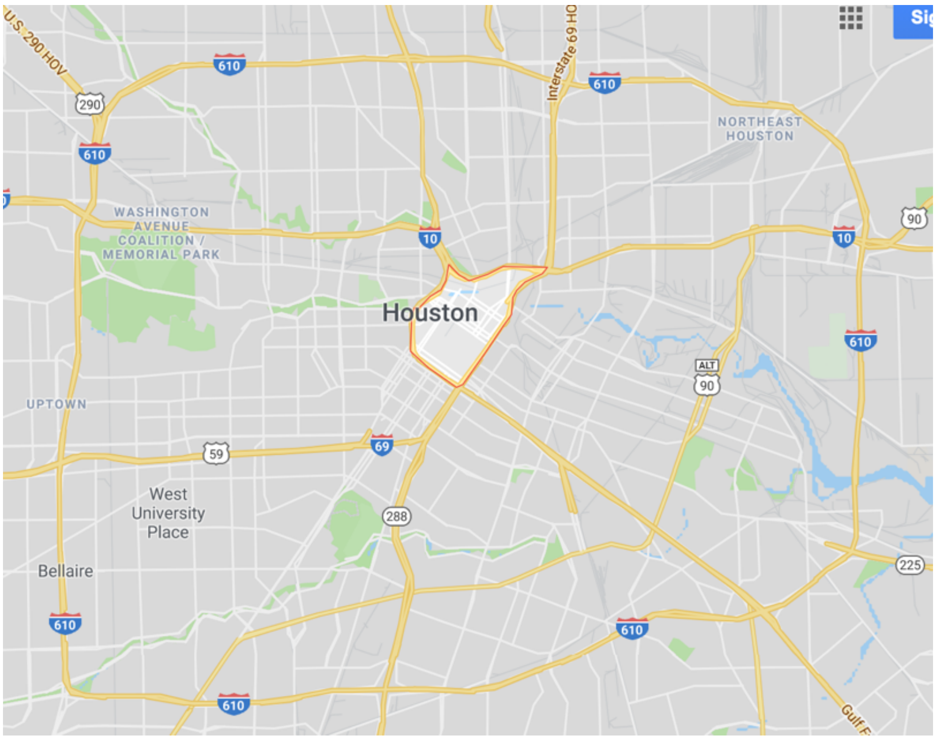

Fig. 3.1 Downtown on a Map of Houston [59]

82% of Downtown employees work in the private sector, many employed by 19 major corporations [11]. Over 20,000 work for the City of Houston [83]. The 20 principal employment centers account for 45% of the jobs in Downtown Houston. Their locations, labelled in order of employment, are illustrated on a map of Downtown in Figure 3.2 and the total employment for each office is written in Table B.1 in the Appendix.

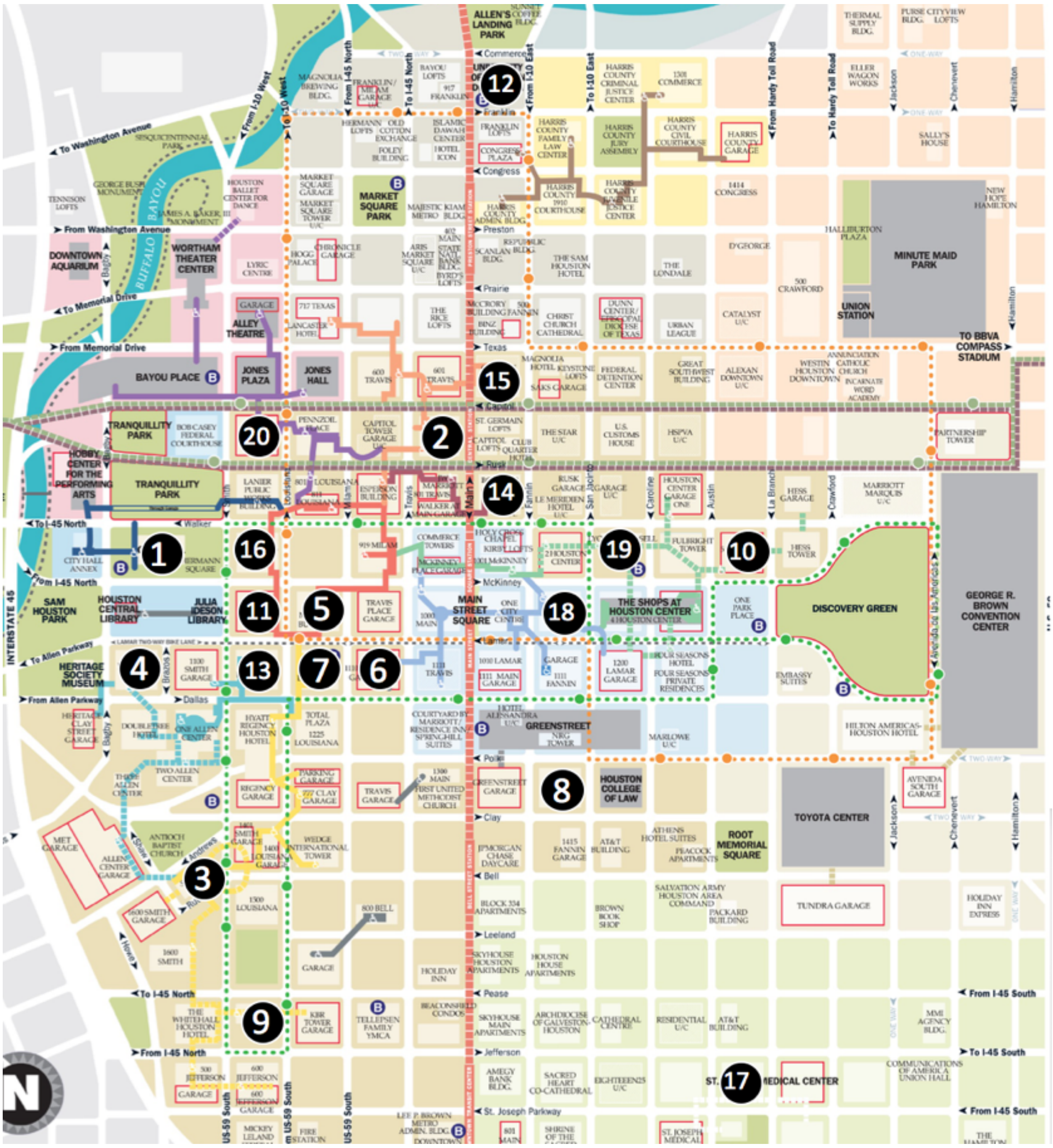

Fig. 3.2 Top 20 Employers in Downtown Houston Numbered from Most Employees to Least Employees [83] [59]

Beyond employment, Downtown Houston is a destination for 10 million visitors each year and home to professional sports teams, Broadway musicals, theatre and ballet performances, an aquarium, and 342 retailers [11].

Due to its high-density employment and the influx of visitors each year, transport is a priority for many governmental and transportation organizations, including the Downtown District, Central Houston, the City of Houston, METRO, and the Texas Department of Transport. The Downtown District states that "improved access and mobility [...] continues to be a major focus" for the area [82]. Therefore, they are open to the idea of autonomous vehicles, imagining "a Downtown featuring electric vehicle charging stations, dedicated lanes for autonomous buses, and pickup and drop-off zones for ride-sharing vehicles and autonomous taxis" [84].

3.2 Demand

There are 150,000 total employees Downtown, 58% of which (87,000) drive to work and therefore represent the demand for the autonomous system [11].

3.3 Existing Transport Options

Downtown is the most connected area of Houston regarding public transport. There are many options for Downtown-goers, including 28 Park & Ride routes, 3 light rail lines, 15 bus routes, 2 circulator buses, taxi cabs, bike rentals, and a 6.5 mile walkable tunnel system [11] [24] [85] [65]. The most utilized options within Downtown are the light rail and buses, so these will be subsequently described. Currently, 32% of Downtown employees (48,000 people) use public transportation and 11.2% (17,000) use alternative modes of transport [11]. This is compared to the 2.4% of public transit users in Greater Houston [11].

3.3.1 Light Rail

Houston hosts 3 METRO-operated light rail lines: red, green, and purple [65]. The light rail lines are shown in Figure 3.3, where the shaded area represents Downtown. The red, green, and purple lines run 2.6 miles, 3.2 miles, and 6.7 miles respectively, for a total of approximately 23 miles, 3.4 of which traverse Downtown [86].

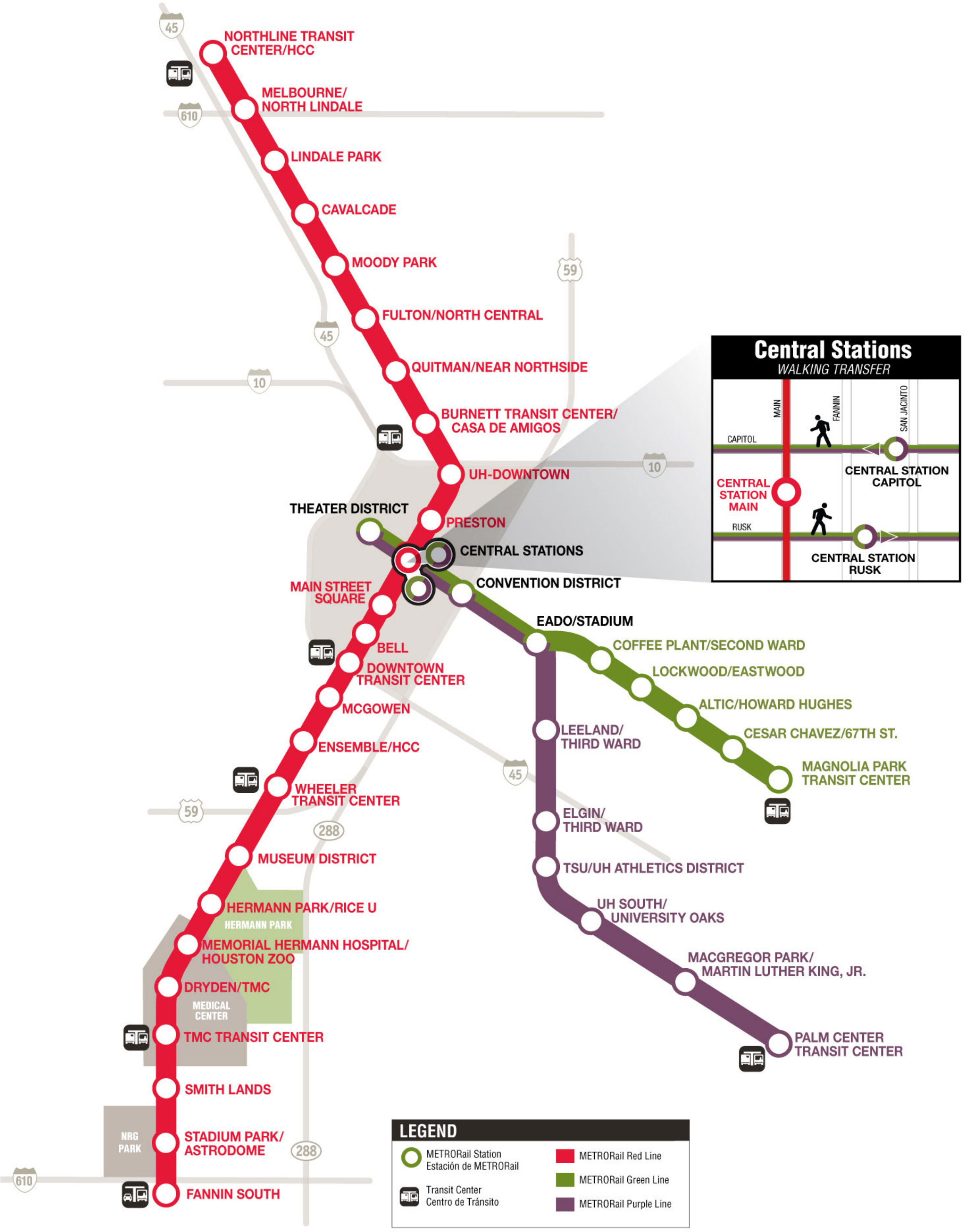

Fig. 3.3 METRO Light Rail Routes [27]

The fare for light rail is $1.25 per ride [65]. The frequency, end-to-end journey time within Downtown, and average weekday ridership within Downtown are detailed in Table 3.1.

Table 3.1 Frequency, End-to-End Journey Time, and Average Weekday Ridership by Route [60] [87] [88]

	Red	Green	Purple
Frequency	6 mins	12 mins	12 mins
End-to-end Journey Time	10 mins	8 mins	8 mins
Daily Ridership	13,900	1,900	2,300

System-wide light rail ridership has declined 4% over the past year [64]. Despite this decline, the red line boasts one of the best ridership rates in the country, surpassing the 2004 ridership goal they set for themselves by 43% [89] [64]. The green and purple lines pale in comparison to the red line in terms of ridership [64]. They do not carry enough customers to justify their spending because they do not service a high enough demand.

Despite the questionable success of the light rail system, Houston has invested large sums of money in it. The year and cost of system installment is summarized in Table 3.2.

Table 3.2 Spending on Light Rail [90] [91] [86] [92]

	Year Opened	Cost	Cost per Mile
Red	2004	$1.08B	$86M
Green & Puple	2015	$1.4B	$140M

Many Houston transport experts claim that light rail is too expensive to be justified and that Houston should look for alternative transit systems [92] [25].

3.3.2 Bus

There are 15 different METRO-operated bus routes that pass through Downtown, illustrated in Figure 3.4 [85]. Each bus ride costs $1.25 [93].

Fig. 3.4 METRO Bus Routes in Downtown Houston [85]

The April 2019 boarding and alightment counts for METRO bus stops within Downtown are detailed in Table 3.3. The total average weekday ridership has decreased by 3% this past year [64].

Table 3.3 Bus Boardings and Alightings for Downtown Stops [69]

Boardings	Alightings
22,600	23,700

The average frequency for the buses is 20.9 minutes [64]. The frequency of the 15 bus routes with stops in Downtown are shown in the Appendix in Table B.2. The current buses stop at every other corner, meaning they are slow but service many locations [93].

3.4 Performance and Service Level Targets

3.4.1 Capacity

The public transportation runs most frequently between 6 and 9 AM, so it was assumed that the morning rush is during this time [64][60][87][88].

$$Average\ peak\ pph = \frac{Total\ riders}{Number\ of\ hours\ in\ peak}$$

$$Design\ hour\ pph = 1.5 \times Average\ number\ of\ riders\ in\ peak$$

This yielded an average pph of 29,000 riders and a design hour pph of 43,400 riders.

3.4.2 Journey Time

Downtown is confined to 1.84 square miles [11]. Imagining that Downtown is a circle with an area of 1.84 gave a diameter of 1.53 miles, which was assumed to be the maximum journey distance Downtown, allowing for employees to be transported from anywhere to anywhere. If the 30 mph pods travel at an average speed of 20 mph to take stopping and turning into account, each ride would take 4.6 minutes or less. It was assumed that passengers need at most 50 seconds to load and 50 seconds to unload, making the maximum single trip journey time 6.3 minutes. The energy requirement was estimated as .17 kWh/km. The battery capacity was estimated as 17.6 kWh with a charge rate of 22 kW [94]. Using these estimates, a pod would use 3% of its battery capacity for each trip taken, meaning it would take 33 trips in 3.4 hours before needing to charge. This covers the entire morning rush hour. For this, the pod charge time did not need to be taken into account. The total journey time compared to that of a car and light rail is shown in Figure 3.5.

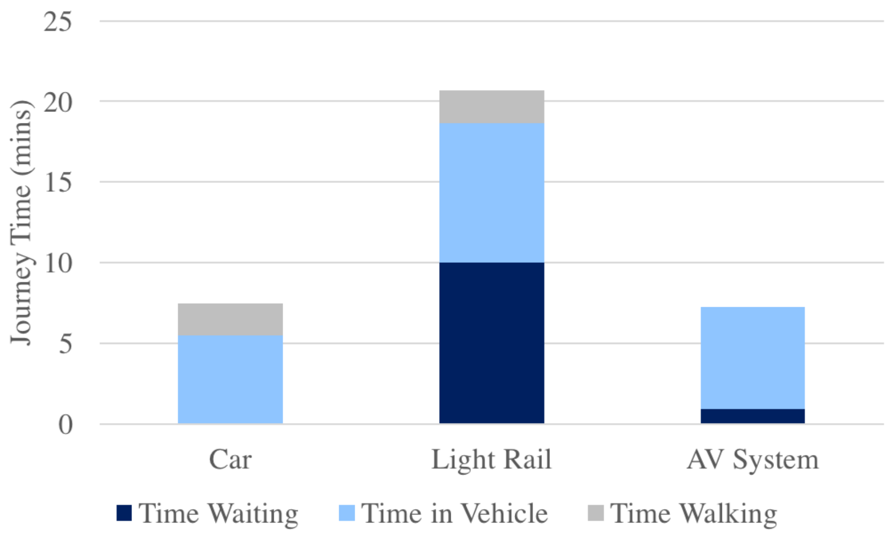

Fig. 3.5 Single Journey Time Including Maximum Wait, End-to-end In-Vehicle Time, and Maximum Walking Time Comparison by Mode

The driver would not need to wait for a vehicle, while the maximum waiting time for the car and light rail were determined by the system frequency (shown in Section 3.4.3).

The pod system would not require walking time because the autonomous system would take riders from anywhere to anywhere, whereas the driver would park in a garage before walking from the garage to work and the light rail user would walk from the drop-off station to their workplace.

3.4.3 Frequency

The popular Downtown employers are clustered in a dense area of .2 square miles, shown on Figure 3.6 [83].

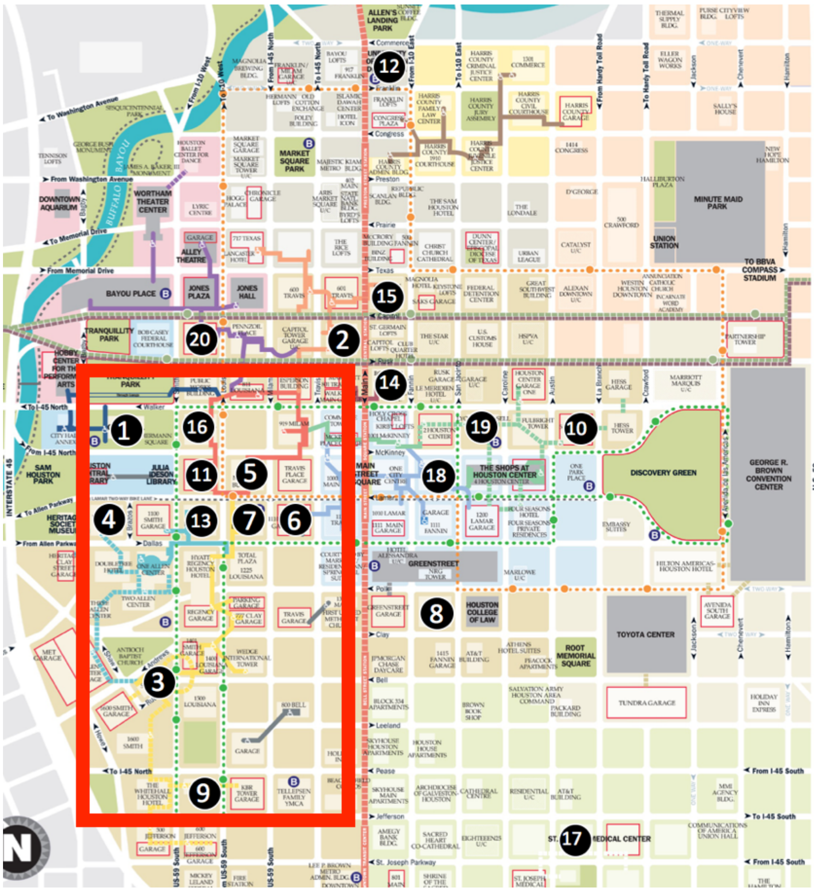

Fig. 3.6 Most Popular Downtown Employers on Map of Downtown with Dense Employer Area Marked [83]

For this, it was assumed that the pods would be distributed unevenly. Estimating that 2/3 of the pods would be clustered in the densely-populated .2 square miles and 1/3 would roam the rest of Downtown at any given time gave a worst-case scenario for the wait time for a pod to arrive to a rider's location. The pod density in the sparse area was found (174 pods/square km). The journey would be 6.3 minutes long with 50 seconds dedicated to the unloading of a passenger. Taking this unloading time as a percent of the total journey (13.2%) showed how many pods unload at any given moment (23 pods). This means that there would be one pod unloading for every .04 square km. Assuming the rider and the pod are at opposite ends of the square kilometer means that, at most, the pod would travel .06 km to get to the rider, which would take 6 seconds. In the worst-case scenario, the pod would have just begun to unload, so a would-be passenger would wait 50 seconds for the pod to unload and then wait for the pod to travel to them. This amounts to a wait time or frequency of 56 seconds.

3.5 Routes and Infrastructure

3.5.1 Routes

Employees drive into Downtown from 6 major highways and 47 roads that feed into Downtown from every area in Houston [7] [23] [85]. Then, these employees head to their place of work, distributed over 3,000 businesses that call Downtown their home [82]. This distributed network requires a system that can transport customers from anywhere to anywhere. For this, the routes were determined to be demand-responsive, flexible routes rather than fixed routes. This means that the Downtown system would follow the Mobility as a Service model where customers can use smart phones to hail rides.

3.5.2 Infrastructure

Downtown would be closed off for the exclusive use of the AV system. Therefore, the pods would be free-roaming without the need for segregated lanes. There would be 6 pod stations at the perimeter of Downtown where the 6 major highways feed into Downtown. The stations would include charging infrastructure.

3.6 Vehicle Fleet

3.6.1 Vehicle Size

The current bus system has a comprehensive but slow and infrequent Downtown network. The light rail system is too expensive for the relatively small demand that an expansion of the system would capture.

The light rail vehicle capacity is 150 individuals during crowded peak conditions, while the capacity of the buses range from 34 to 57 individuals [69]. As shown in Tables 3.1 and B.2, the frequencies for the different light rail and bus routes range from 6 to 60 minutes

[60] [87] [88] [64]. More frequent services could be provided if Downtown offered smaller transit vehicles.

Small, flexible-route vehicles are conducive to a fast, frequent, anywhere to anywhere system. For this, 4-seater and 2-seater vehicles were initially proposed. The average vehicle occupancy in the United States is 1.1 people per vehicle for work trips and 2.1 people per vehicle for social or recreational purposes [95]. The autonomous pod system would be adopted more smoothly if it avoids challenging social norms. For this, 2-seater pods would be advantageous for Downtown because customers would not need to share their ride with more than one other passenger. This is in line with the current norm of driving alone or with one other person. In addition, vehicles with fewer passenger can take more direct journeys without deviating from the path in order to pick up or drop off more passengers.

On the other hand, 4-seater vehicles could better serve groups of people coming into Downtown who might resent splitting up the group because of a lack of larger cars. For social or recreational journeys, 70% of the trips would have 1-2 passengers while 30% would carry 3-4 to give an average of 2.1 per vehicle. It was assumed that 25% of Downtown employees would use the pod systems for lunch (a recreational purpose) while 57% (75% of those who currently drive) would use the pod systems for commuting. Even counting the 27,000 daily visitors, more people enter downtown each day for commuting purposes than for social purposes. Using this informamtion, the question of which system would be better must be answered: 2-seater pods to favor the commuters or 4-seater pods to favor the visitors and lunch-goers.

Furthermore, the smaller pods would be less energy intensive than the larger pods, shown in Table 3.4. The energy intensity includes energy for movement and AC use.

Table 3.4 Energy Intensity of 2-Seater and 4-Seater Pods

	2-Seater	4-Seater
Energy Intensity (kWh/km)	.17	.25

In the first scenario, the system of 2-seater pods would service the commuters in the morning, running with 1 or 2 people per pod. If a group of work friends wants to go to lunch together or a family of 4 wants to visit the Downtown Aquarium, they would need to split their group to take multiple pods. The advantage is that the pods would generally run at full capacity and therefore have fewer emissions per passenger kilometer. The disadvantage is that big groups would split up.

In the second scenario, the system of 4-seater pods would service the commuters in the morning, running with 1 or 2 people per pod. The advantage is that the pods could fit larger groups, but the disadvantage is that the average load factor would be low because the pods would generally run at half capacity. For this, there would be greater emissions per passenger kilometer. Figure 3.7 summarizes the emissions per passenger kilometer of a 2-seater pod running at full capacity, a 4-seater pod running at full capacity, and a 4-seater pod running at half capacity.

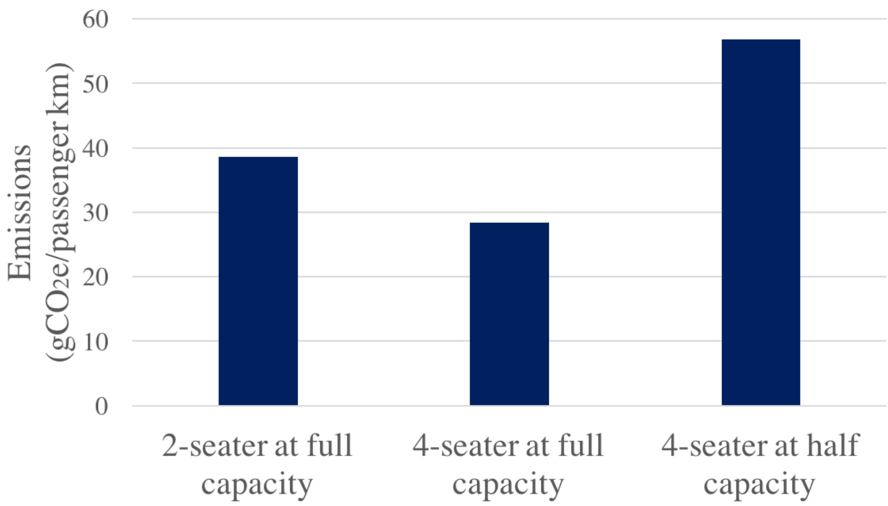

Fig. 3.7 Emissions of 2-Seater at Full Capacity and 4-Seater at Full and Half Capacity [76]

Assuming that the 2-seater system generally runs at full capacity and the 4-seater system runs at half capacity for commuters, half capacity for 70% of social trips, and full capacity for 30% of social trips yielded the total emissions per passenger kilometer of each system. Aggregating this over a year using the total kilometers the pods travel daily gave the total annual emissions, shown in Figure 3.8.

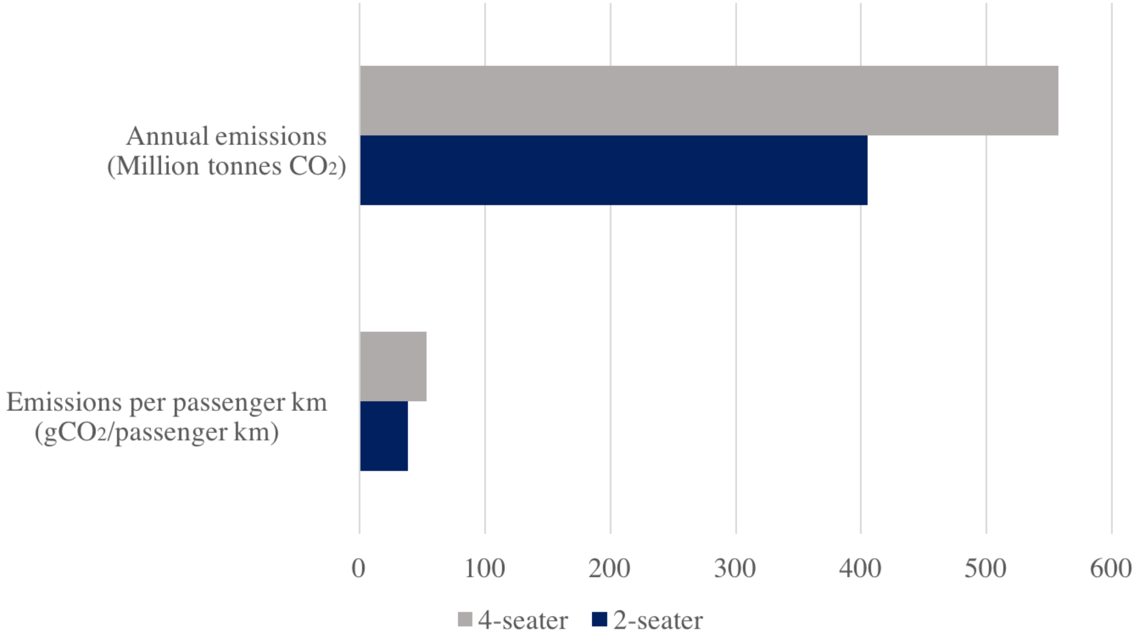

Fig. 3.8 Average Emissions per Passenger Kilometer and Annual Emissions of a 2-Seater and 4-Seater System [76]

The energy penalty of the 4-seater pod system would be a 40% increase in annual emissions when compared to the 2-seater pod system. As shown in Figure 6.1, the transportation proposal for Houston should balance economic, environmental, and social reasons. The social inconvenience of splitting up occasional groups of 3+ people is worth the environmental benefit of fewer emissions associated with running small vehicles at higher load factors. For this, 2-seater pods were chosen for the Downtown system, shown in Figure 3.9.

Fig. 3.9 Daimler 2-Seater Pod [96]

Customers could call these on-demand driverless vehicles using an app on their phone, the vehicle would arrive immediately, and the customers would be transported directly to their place of work, possibly stopping to pick up another rider. These vehicles would be level 4 driverless vehicles that roam the streets, interacting with pedestrians and observed by remote operators who could intervene in the case of an emergency.

3.6.2 Number of Vehicles

The fleet was sized to reflect the design hour pph.

$$Number\ of\ pod\ departures\ needed = \frac{Design\ hour\ pph}{Capacity\ of\ pods}$$

This yielded 22,000 design hour pod departures. These numbers are summarized in Table 3.5.

Table 3.5 Total Peak Ridership, Average Peak Rishership per Hour, and Design Hour Ridership

Peak Ridership	Average Peak pph	Design Hour pph	Pod Departures Needed
87,000	29,000	42,000	22,000

Though many pod departures would be needed, the pods could run multiple circuits in an hour. For this, the fleet size would be far smaller than the number of pod departures needed.

If the trip journey time were 6.3 minutes, the pods could take 9.6 circuits per hour, yielding a fleet size of 2,221 vehicles.

$$Fleet\ size = \frac{Design\ hour\ pod\ departures}{Circuits\ per\ hour}$$

Congestion

This system would require a large fleet size and therefore should be benchmarked against current traffic to decide whether this multi-vehicle system would cause too much congestion. The mobility strategy would ban personal vehicles from driving within Downtown except in extraneous circumstances. For this, it was assumed that pods would be the only vehicles traversing Downtown.

87,000 people drive to work each day with an average of 1.1 people per vehicle [11] [95]. This means 79,000 cars come into Downtown each day spread out over a 3 hour morning rush hour, yielding an average of 26,000 cars coming in per hour. The design hour usually sees an increase in traffic of 1.5x the average, so 39,000 cars flow into Downtown in the design hour.

The autonomous system would require 22,000 pod movements during the design hour, a 45% reduction in vehicle movements based on current levels. In addition to a decrease in the number of vehicle movements, the vehicles roaming the roads would be smaller. A 2-seater autonomous vehicle, Daimler's Smart EQ forTwo, and a typical car, a Toyota Corolla, are pictured with their dimensions in Figure 3.10. The AVs would be smaller, thus causing a reduction in congestion volume of 64%.

Fig. 3.10 Smart EQ forTwo and Toyota Corolla Dimensions [97] [94]

Further reductions in congestion could be made by increasing the size of the autonomous vehicles that service the top employers' offices. 20-passenger and 10-passenger pods were analyzed as options for the transport of employees to the top 20 employers, listed in Table B.1. Downtown employees arrive from 6 different highways, so it was assumed that they would congregate at 6 different arrival lots [7] [23]. The percentage of total people commuting into Downtown arriving from a particular highway was used to determine how many people would arrive at each lot. It was also assumed that the employees for the large employers would be evenly distributed across the 6 different lots. The frequency of pods leaving from each of these arrival lots would range from 1 to 23 minutes for the 20-passenger shuttles or .5 to 11 minutes for the 10-passenger shuttles. The frequencies of the 20-passenger and 10-passenger pods are summarized in the Appendix in Table B.3.

Frequency can be sacrificed in order to decrease congestion. The 20-passenger pods would have too long of wait times to be desirable. It would be possible for the top 6 employers to operate 10-passenger pods with frequencies of 5 minutes or less. This would cause 4,000 fewer vehicle movements in the design hour, a 19% decrease in vehicle movements compared to using all 2-seater pods. Though this would reduce congestion more than the 2-seater system, this report examines the use of a system of 2-seater pods.

3.7 Economics

Vehicles

The fleet would consist of 2,221 pods estimated to have an upfront cost of $30,000 paid back over a period of 10 years at a 4% interest rate. The annual cost of the vehicles would be $8,095,000.

Infrastructure

It was estimated that the pod stations would incur costs of $1,000,000 paid back over 10 years at an interest rate of 4%. The annual cost of the infrastructure would be $121,000.

Fuel Consumption

It was assumed that the pods would operate for 8 hours a day to meet commuters' needs: 3 hours in the morning peak, 2 hours in the lunch peak, and 3 hours in the evening peak. Using these hours of operation, the total kilometers per day that all the pods would travel was calculated. The pods were estimated to use .15 kWh/km for movement and .5 kW of cooling power, which translates to .02 kWh/km for air conditioning. Using the total kilometers per day travelled and the total energy requirement of .17 kWh/km gave the daily fuel consumption, which was then used to find the annual pod electricity consumption.

$$Annual\ fuel\ consumption = .17kWh/km \times total\ daily\ km \times 7\ days/week \times 52\ weeks/year$$

The average cost of electricity per kWh for the transportation sector in Texas in the past year was 7.44¢/kWh [71]. Multiplying this by the annual electricity consumption gave the annual cost of fuel consumption, $1,070,000.

$$Annual\ cost\ of\ fuel\ consumption = Average\ price\ of\ fuel \times Annual\ fuel\ consumption$$

Staff

Remote operators would be necessary for the operation of the AV system. The remote operators were assumed to be responsible for watching 5 pods at a time. At all times, it was assumed that a shift manager and secretary were neccesary. In addition, it was assumed that one mechanic was needed per every 10 pods running. It was also assumed that information staffers were manning the streets as customer service representatives. The safety critical team of the remote operators, secretary, and shift manager would require 151 square feet of office space per person (the US average) [72]. It was assumed that the office space would cost $31.34 per square foot (the Houston average) [73]. Every employee was assumed to make $35,000 per year. The annual cost of staff would be $25,642,000.

Lunchtime Use

Lunchtime

The map of Downtown in Figure 3.11 denotes the 20 major employers (black circles numbered from most to least employees); main food halls, shopping malls, and grocery stores (large red circles); and restaurants (small red circles).

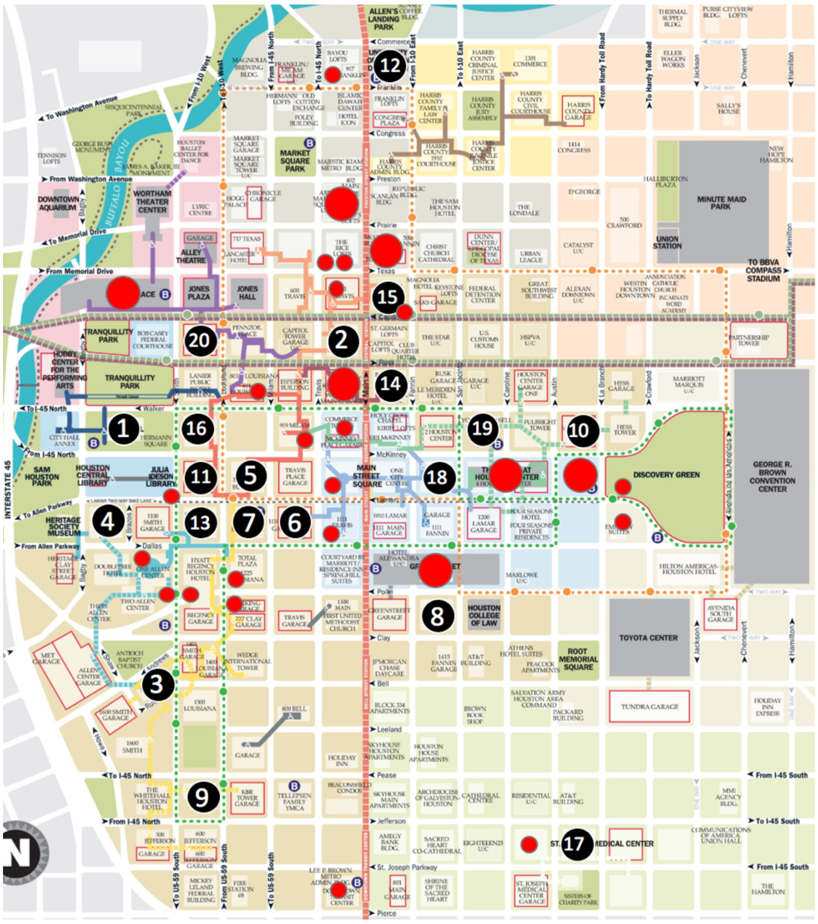

Fig. 3.11 Biggest Employers and Employee Lunch Spots in Downtown [83][59]

Routes were drawn from City Hall, marked as number 1 on the map, to each lunch spot. Each city block is 350 feet square [59]. Assuming people walk 5 ft/s, it would take someone 70 seconds to walk the length of one city block. It was assumed that people would walk or drive no longer than 5 minutes to get to lunch because, for a 30 minute lunch break, a 10 minute round trip journey was assumed to be the upper bound that people would be willing to travel. This means that they could walk the length of 4 city blocks (denoted by a purple circle with a radius of 4 blocks) or drive a radius of 20 city blocks (covering all of Downtown). Figure 3.12 shows the restaurants denoted by purple circles that are within walking distance of City Hall (the top employer), whereas all the other restaurants (denoted by red circles) are within driving distance. The system would benefit Downtown employees along with Downtown restaurants, food halls, and malls.

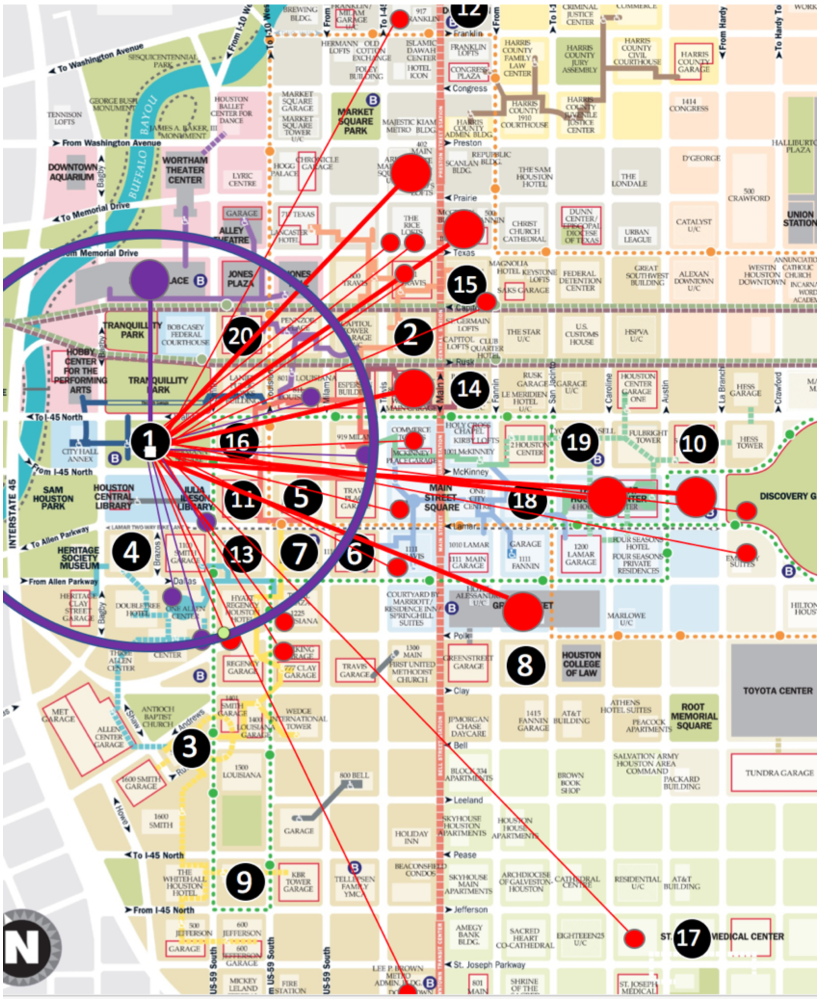

Fig. 3.12 Biggest Employers and Employee Lunch Spots

The income from pod usage during lunchtime would be very valuable because it would generate more revenue without much additional capital investment. If the pods were not used during lunch, they would loiter unused. The energy requirement of the lunchtime rush was calculated and used to update the cost of fuel consumption. The breakeven cost per single ride was calculated by dividing the total annual costs of the system by the number of rides taken annually.

$$Breakeven\ cost\ per\ ride = \frac{Total\ annual\ cost\ of\ system}{Total\ annual\ rides}$$

The number of lunchtime trips would affect the breakeven cost per ride. The more lunchtime pod users, the less the breakeven cost per ride. It was assumed that 50% of Downtown employees go out for lunch and 50% of those employees use pods to get to lunch, thus yielding a 25% rate of pod use during lunch hours.

3.7.1 Summary of Costs

The costs of the system are made up of many components already discussed: the cost of the vehicles, infrastructure, fuel consumption, and staff. The summary of the component costs is presented in Table 3.6. In order to find the breakeven cost per single ride, it was assumed that 75% of the Downtown employees that currently drive to work would be captured by the proposed AV system and 25% of all Downtown employees would take pods to lunch.

Table 3.6 Summary of Downtown Autonomous System Costs

Cost Description	Cost
Vehicles	\$8,095,000
Infrastructure	\$121,000
Fuel Consumption	\$1,070,000
Staff	\$25,642,000
Total Annual Costs	\$33,175,000
Breakeven Cost Per Ride	\$0.63

The cost breakdown for the Downtown AV system is shown in Figure 3.13.

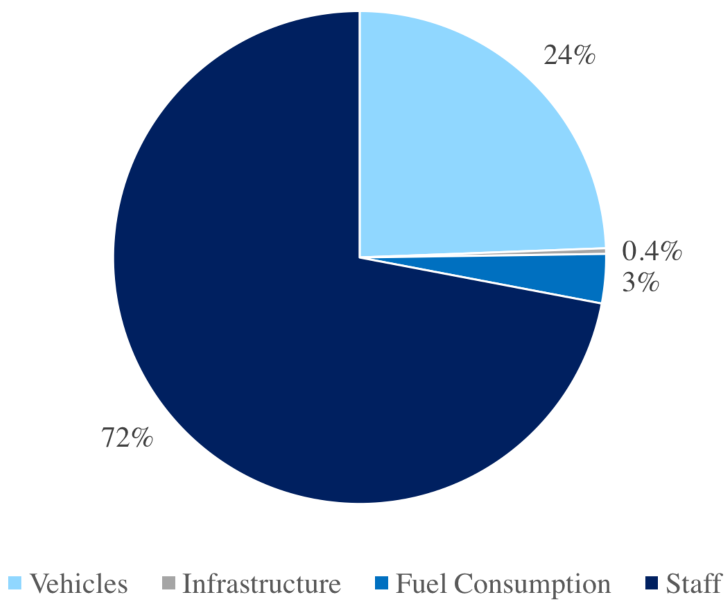

Fig. 3.13 Downtown AV System Cost Breakdown

3.7.2 Sensitivity Analysis

Different inputs to the model were varied to determine the effect of the different variables on the annual price of the AV system and the breakeven cost per single ride. The inputs varied were upfront vehicle cost, interest rate, electricity price, ratio of remote operators to pods, and fraction of lunchtime pod users. The high, medium, and low estimates for each input are summarized in Table 3.7. Effects of the varied inputs on specific costs components are found in Appendix B.

Table 3.7 Low, Medium, and High Estimates for Sensitivity Study Inputs

Input	Low Estimate	Medium Estimate	High Estimate
Vehicles	\$30,000	\$50,000	\$70,000
Interest Rate	4%	6%	8%
Electricity Price	6.25 ¢/kWh	7.44 ¢/kWh	8.46 ¢/kWh
Remote Operators:Pod Ratio	1:5	1:20	1:50
Lunchtime Ridership Level	6%	25%	56%

To find the lunchtime ridership level, two assumptions were varied: the number of Downtown employees that would leave their workplace for lunch (25% to 75%) and the number of those employees that would use pods to get to the lunch spot (25% to 75%).

The effects of the sensitivity study on the annual cost of the system and the breakeven cost per single ride are illustrated in Figure 3.14, where each variation is compared to the baseline case.

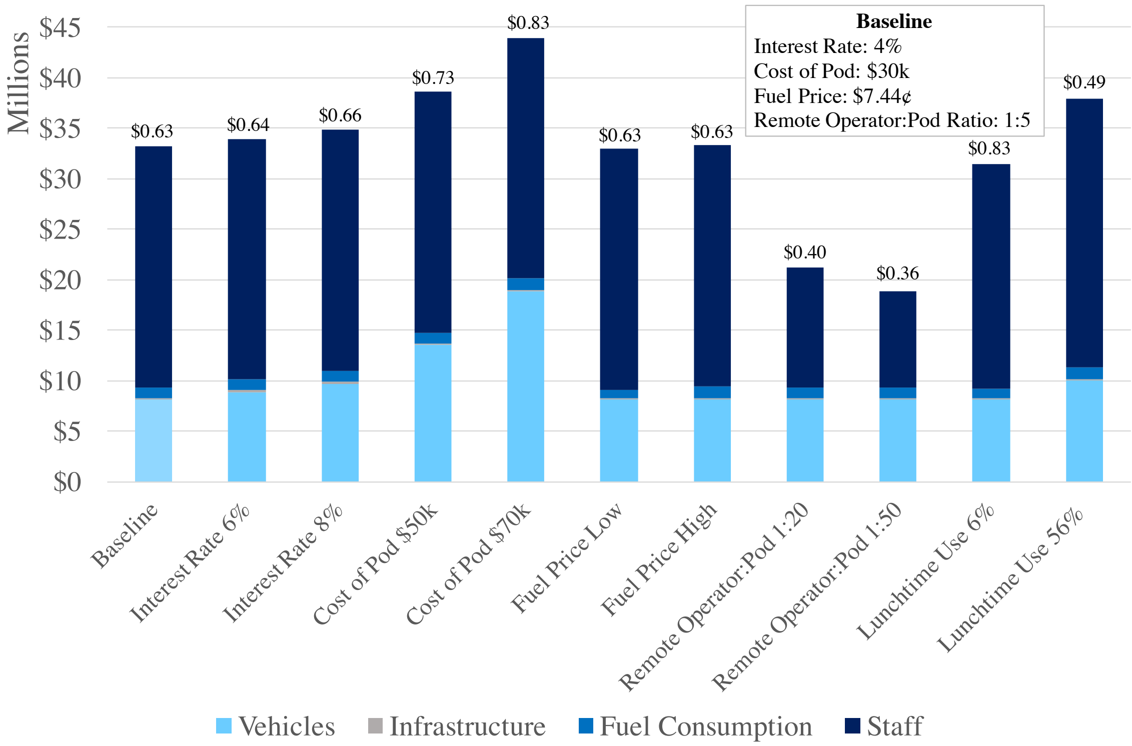

Fig. 3.14 Economics Sensitivity Analysis with Cost Breakdown by Component and Breakeven Cost per Single Ride

The inputs with the biggest impact are cost of the vehicle, number of remote operators required, and lunchtime use fraction.

The staff costs decrease rapidly as the remote operator:pod ratio changes from 1:5 to 1:20, but almost level off between 1:20 and 1:50, shown in Figure 3.15. For this, the ideal ratio would be 1:20 so that there would be increased safety, public approval, and a cheaper price tag.

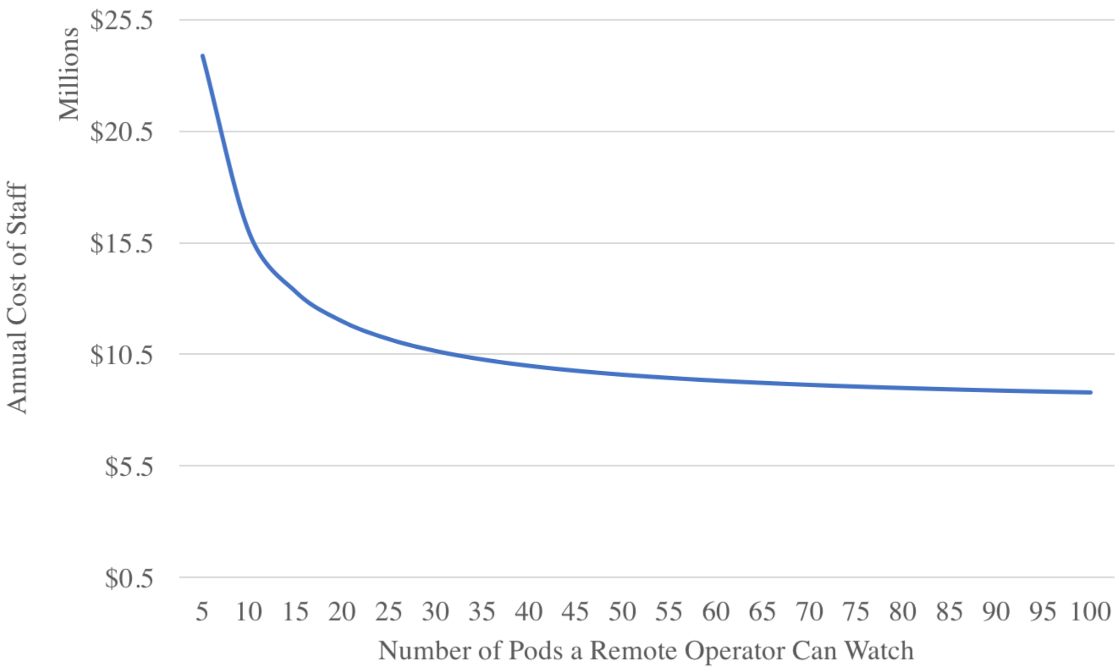

Fig. 3.15 Cost of Staff vs. Number of Pods A Remote Operator Can Watch

The cost of staff levels off because the staff costs of the mechanics, secretary, shift manager, and customer service representatives have a larger weight when fewer remote operators are needed. For this, the goal should be to have a remote operator for every 20 pods to decrease the overall costs of the system.

3.7.3 Economics Comparison

METRO publishes the capital and operating costs of the different transportation systems, including the light rail and bus system. 12% of bus rides and 30% of light rail rides are taken within Downtown [69] [64]. Therefore, it was assumed that 12% and 30% of the capital and operating costs of the entire bus system and light rail system respectively are dedicated to Downtown. These costs, along with the proposed system costs are summarized in Figure 3.16 and in the Appendix in Table B.9.

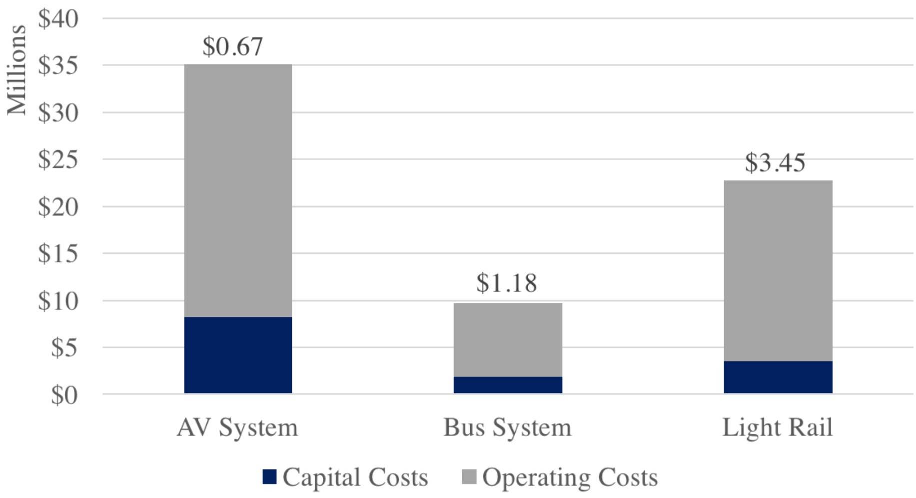

Fig. 3.16 Downtown Cost Comparison by Mode with Breakeven Cost per Single Ride [69]

Though the AV system would be the most expensive annually, it was assumed to capture the most riders (75% of Downtown commuters that currently drive and 25% of Downtown employees for lunch) and therefore would have the cheapest breakeven cost per single ride.

The autonomous system breakeven cost per ride always beats that of the light rail system. Assuming constant lunchtime ridership of 25%, the autonomous system must exceed 20% commuter ridership levels to have a cheaper breakeven cost per single ride than the bus system, shown in Figure 3.17.

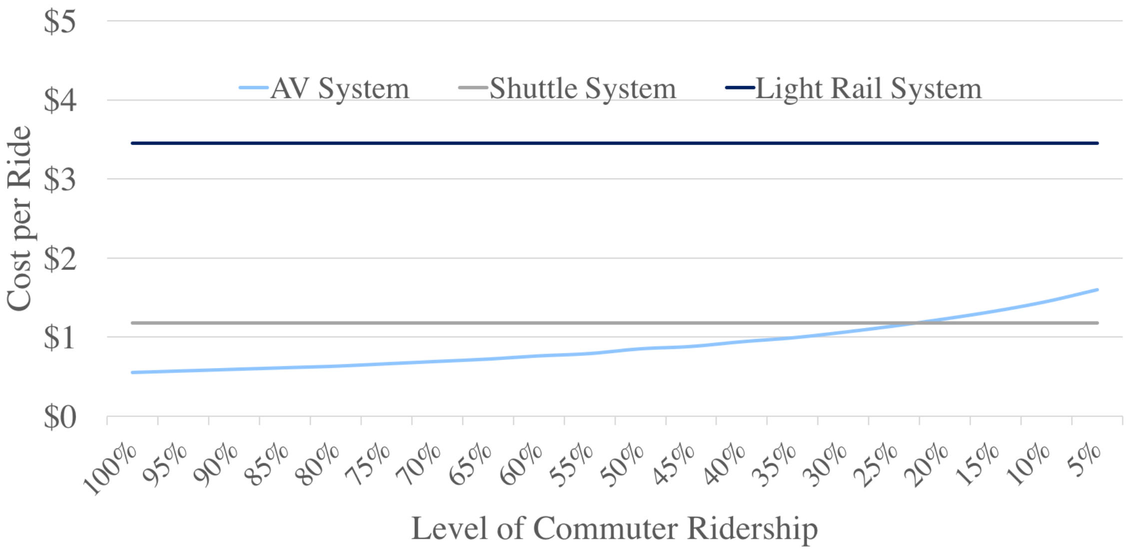

Fig. 3.17 Breakeven Cost Per Single Ride vs. Assumed Commuter Ridership Level with Breakeven Cost per Ride of Light Rail and Shuttle Systems

3.7.4 Financial Viability

The assumptions used to calculate the financial viability of the Downtown system are summarized in Table 3.8.

Table 3.8 Assumed Final Ridership Level, Fare, and Growth Rate

Final Ridership Level	Fare	Growth Rate	Time Period
75%	$1.25	year 1: 50% final ridership year 2: 80% final ridership year 3+: 100% final ridership	10 years

The costs, revenues, profits, and cumulative profits for each year over a period of 10 years are presented in Table B.10 in the Appendix. Figure 3.18 shows the cumulative profits over the 10 year period. This graph presents the initial capital outlay ($67.6 million) as the first point of the graph, the payback period (29 months) as the point where the graph crosses the x-axis, and cumulative profits after the 10 year period ($275 million) as the end point of the graph.

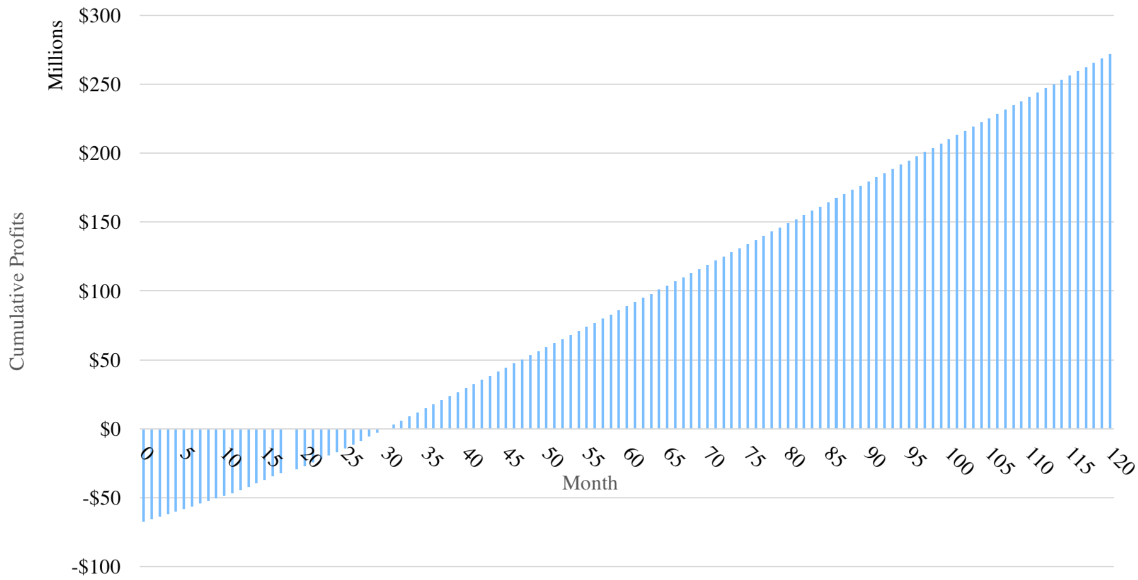

Fig. 3.18 Cumulative Profits of AV System Over 10 Year Period with $1.25 Fare, 75% Final Ridership, and 3 Years to Reach Final Ridership Level

The ROCE over the 10 year period is presented in Figure 3.19. The ROCE stabilizes at 43%, much higher than the average ROCE for non-financial corporations in the UK (12.3%) [75]. The ROCE is most likely so high because the system was assumed to capture so many riders, therefore taking in a lot of revenue. If instead the ROCE were calculated based on current Downtown public transit ridership levels, 32%, the ROCE would stabilize at the more reasonable value of 9%.

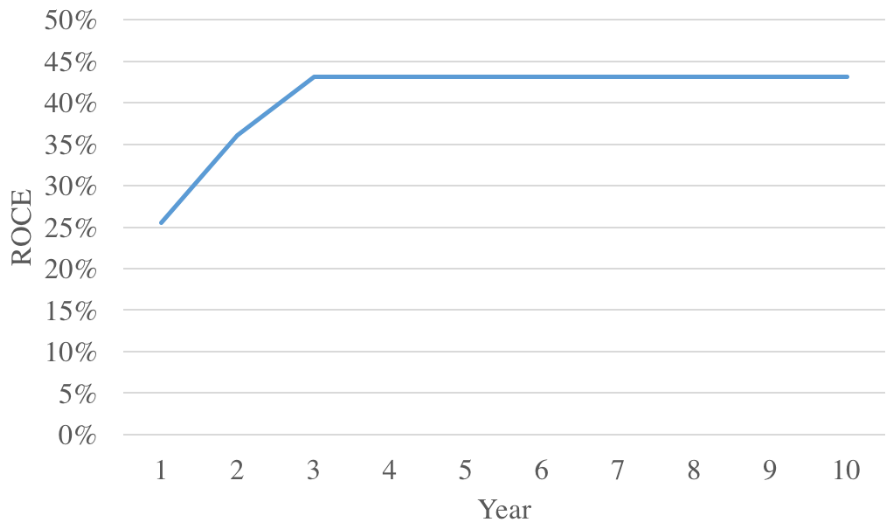

Fig. 3.19 ROCE of AV System Over 10 Year Period with \$1.25 Fare, 75% Final Ridership, and 3 Years to Reach Final Ridership Level

3.7.5 Sensitivity Analysis

The fare price, ending ridership level, and ridership growth were varied and the effects are illustrated in Figures 3.20 and 3.21.

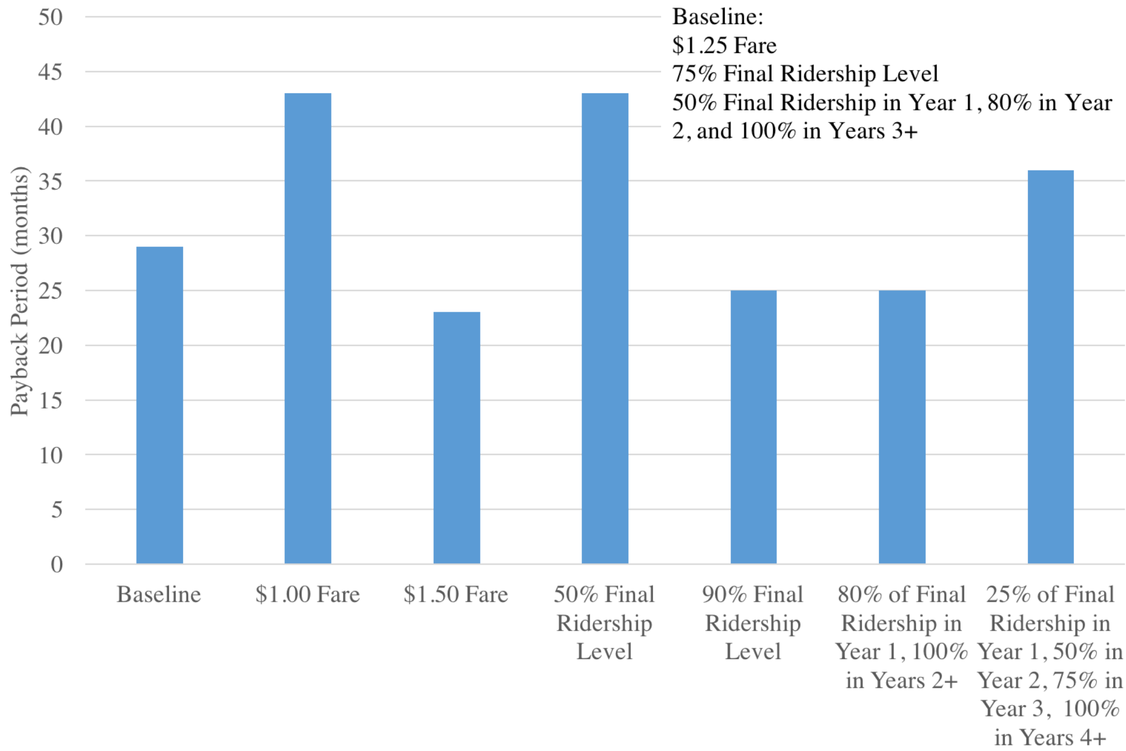

Fig. 3.20 Payback Period Sensitivity Analysis Baseline, Varied Fare, Varied Final Ridership Level, and Varied Ridership Growth

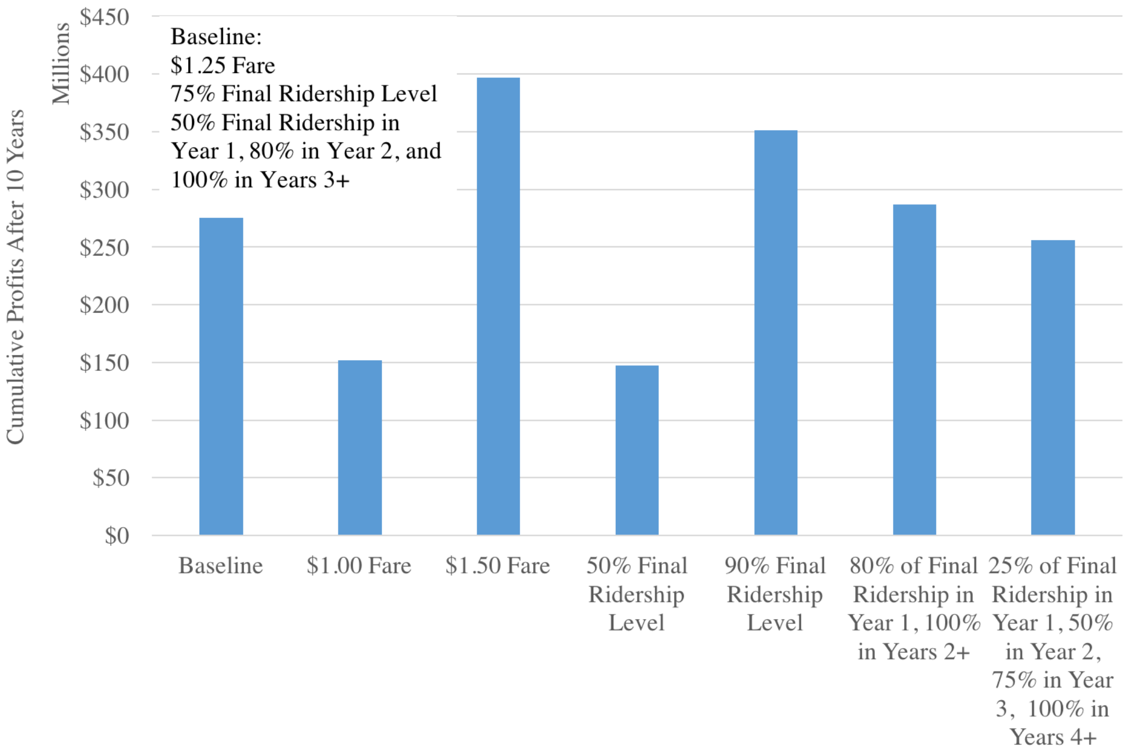

Fig. 3.21 Cumulative Profits After 10 Years Sensitivity Analysis Baseline, Varied Fare, Varied Final Ridership Level, and Varied Ridership Growth

The fare price and final ridership level have the largest effect on the profitability of the system. The different variations tested are subsequently described.

Fare Price

The threshold for the system to be profitable yielded a breakeven fare price of $0.69. The fare was assumed to be priced the same as the current transit option ($1.25), but it could be priced lower ($1.00) to compete with the existing transit or priced higher ($1.50) to make the system more profitable [60].

Final Ridership Level

The threshold for the system to be profitable is 22% ridership, which is double the 11% ridership level of existing Downtown transport [11]. The final ridership level was varied between 50% as the lower bound, 75% as the reasonable baseline, and 90% as the optimistic target for the sensitivity analysis.

Ridership Growth

For the baseline scenario, it was assumed 50% of final ridership numbers for year 1, 80% for year 2, and then 100% for year 3 and onwards. A more optimistic scenario assumed faster uptake in ridership with 80% of final ridership numbers for year 1 and 100% for year 2 onwards. A less optimistic scenario assumed a slower uptake in ridership with 25% of final ridership numbers for year 1, 50% for year 2, 75% for year 3, and 100% for year 4 onwards.

This financial analysis suggests that the Downtown system has the potential to be self-financing via farebox revenues over a 10-year loan period if it surpasses a $0.69 fare price or 22% final ridership levels.

3.7.6 Financing Solution

Ideally, public transportation could service all of Downtown Houston and personal vehicle travel would be banned except in extreme cases. For this, all the space currently used for parking would be freed up and used for something more productive. The Downtown district could finance this project by replacing parking lots and garages with office, residential, or retail space. Currently, much space Downtown is dedicated to the 60 parking garages and 64 surface lots in Downtown, shown in Figure 3.22.

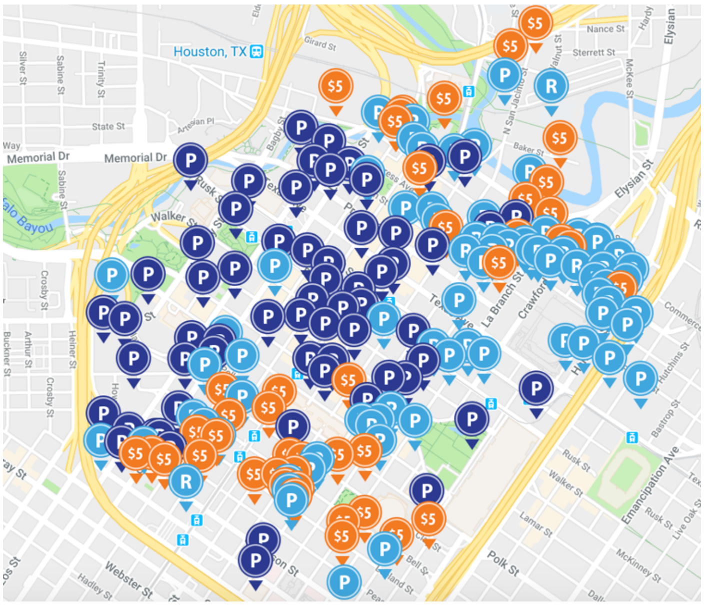

Fig. 3.22 Downtown Parking Garages and Surface Lots on Map of Downtown [98]

The parking requirement necessitates 2.5 parking spaces for every 1,000 square feet of office space [99]. Due to the 50 million square feet of office space, this means that there must, at minimum, be 125,000 parking spaces Downtown that could be replaced and the rent used to finance the AV system [11].

3.8 Emissions

In Texas, 476 gCO_2e are emitted for every kilowatt hour of electricity generated [76]. The proposed pod system was assumed to need .17 kWh/km, the breakdown of which is illustrated in Figure 3.23.

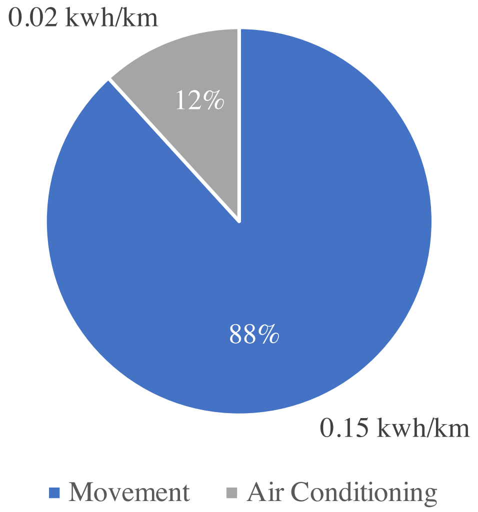

Fig. 3.23 Energy Breakdown of 2-Seater Pods

The energy requirement means the pods would emit 41 gCO_2e/passenger km. This is compared to the emissions from buses and light rail, shown in Figure 3.24 and in the Appendix in Table B.11.

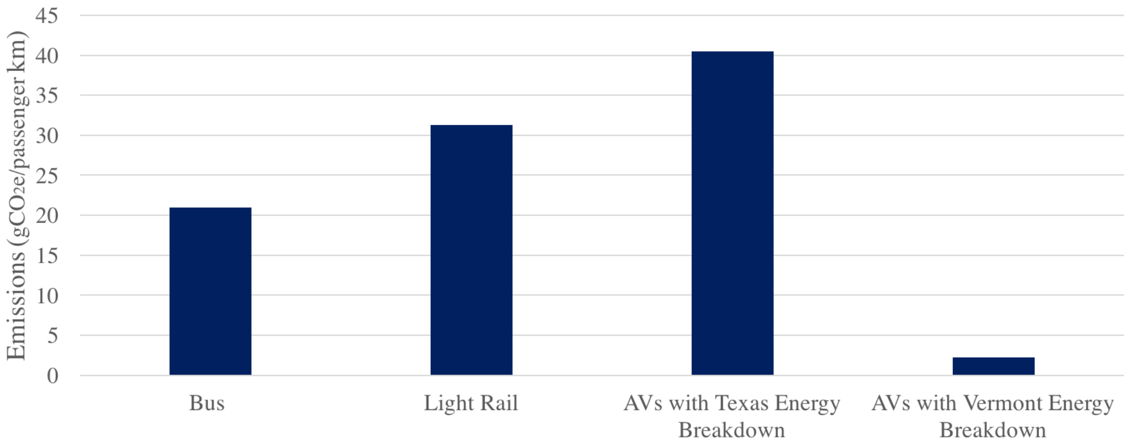

Fig. 3.24 Emissions Comparison by Mode [80] [78] [79]

The AV system would yield the highest emissions per passenger kilometer due to the low number of passengers per vehicle, the high energy requirement for air conditioning (12% of the total energy requirement), and the conservative energy requirement estimates used. A sensitivity analysis that examines the effect of lower energy requirements on emissions is detailed in the subsequent section. Despite the high emissions, the AVs would be part of an integrated public transit system that could encourage people to abandon their cars in favor of public transport, thus decreasing overall transport emissions. These emissions correspond to Texas' current breakdown of electricity generation by source, summarized in Figure 2.27 [77]. As electricity generation shifts from fossil fuels to nuclear and renewable sources, the emissions associated with the electric vehicles would decrease. If Texas were to have the energy breakdown of the lowest emitting state, Vermont, the emissions would decrease to 2 gCO_2e/passenger km [77].

3.8.1 Sensitivity Analysis

The estimate that the pods use .17kWh/km is a conservative estimate. In reality, the energy requirement could range from .09 kWh/km to .18 kWh/km. The energy requirement was initially calculated by estimating and varying the different energy requirement parameters (energy required for movement and energy required for air conditioning), outlined in Table 3.9.

Table 3.9 2-passenger AV Energy Requirement Estimates

Parameter	Energy Requirement	
	Low Estimate	High Estimate
Movement	.1 kWh/km	.15 kWh/km
Air Conditioning	.5 kW	1 kW

The total energy requirement per kilometer for the 4 different combinations of these parameters was calculated. This energy requirement range (.12-.18 kWh/km) is inclusive of real energy requirements for 2-seater autonomous electric vehicles. The Daimler Smart EQ forTwo is one such vehicle with an energy requirement of .129-.135 kWh/km [94].

Next, the energy requirement of a Nissan Leaf was scaled to estimate that of a pod. The Nissan Leaf quotes its energy requirement as 30 kWh/100 miles [100]. Converting yields .186 kWh/km. Assuming that the energy requirement of these vehicles scales with mass and the autonomous vehicles are approximately half the mass of a Nissan Leaf yields a pod energy requirement of .093 kWh/km.

The energy requirements were then multiplied by the carbon emissions per kWh for the Texas electricity supply and divided by two passengers, assuming the pods run full. This yielded the emissions per passenger kilometer, detailed in Figure 3.25 and in Table B.12 in the Appendix.

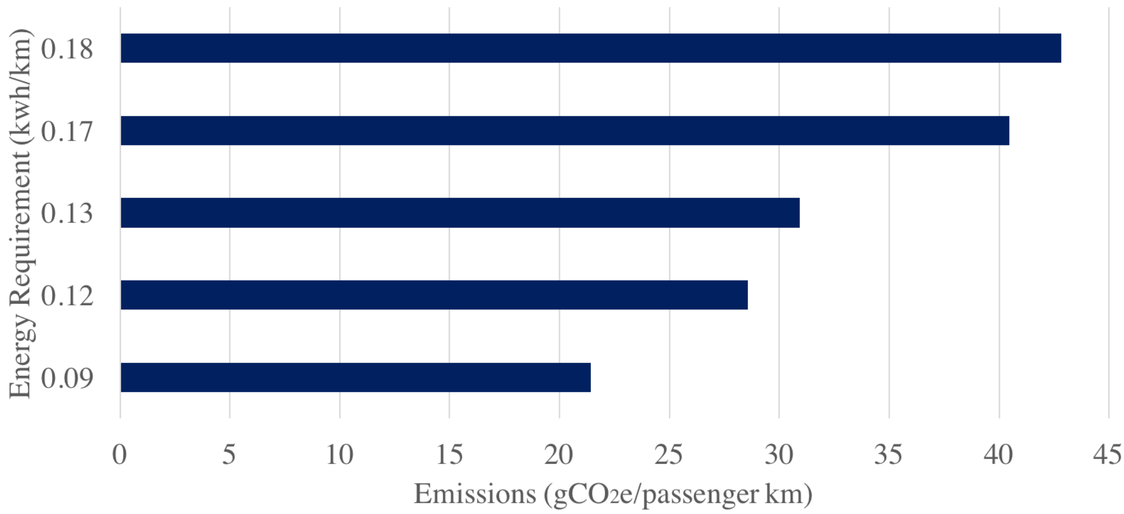

Fig. 3.25 Emissions Sensitivity Analysis

Chapter 4

Transit from Outer to Central Houston

4.1 Suburbs Overview

Houston is a unique major city because spans a large area, is sparsely populated, and the central business district and residential areas are largely separate. Most people who identify as Houstonians do not live within Houston's city limits. The greater Houston area is home to 7 million people, 67% of whom reside in the suburbs outside the boundaries of central Houston [1] [2]. Figure 4.1 shows a map of Houston with central Houston (red inner loop) and the suburban neighborhoods demarcated.

Fig. 4.1 Map of Houston with Suburbs Marked [101]

As mentioned in Chapter 1, most of Houston's commuters drive to work [102]. The negative consequences that Houstonians suffer due to limited mobility solutions will magnify as Houston is expected to grow to 10 million inhabitants by 2040 [4]. While the urban core will remain the job center, 80% of new Houstonians are expected to move to the suburbs [103]. Without public transit, current transportation infrastructure will be overloaded. The city of Houston needs a way to transport people from their suburban homes to their workplaces in central Houston.

The commuter neighborhoods are spread out in a circle surrounding Houston, as shown in Figure 4.1. Commuters flow into Houston along the 6 major highways that run like veins into central Houston. This means that Houston needs multiple different routes to service commuters coming in from all different directions.

A public transit system that challenges the dominance of cars and serves the needs of a sparsely populated city is needed for Houston. Houston's lack of density complicates transportation because traditional forms of transit (heavy or light rail) are too expensive to justify for the relatively small number of passengers they would serve. For example, Houston has built light rail that cost $140 million per mile [92]. In order for this system to serve commuters, there would need to be 6 different rail lines with approximately 20 miles of light rail each, amounting to expenditure of $16.8 billion [59]. In order for a high capacity transit system such as light rail to be worth the high costs, it must transport 5,000-10,000 passengers per hour [104]. Because of Houston's relatively sparse population, this threshold would not be surpassed. For example, in Section 5.2.1 it was estimated that, at peak times, just over 2,500 people per hour would travel from the suburb of Sugar Land to central Houston in the morning. Though Sugar Land is one of the largest suburbs, its population does not justify the costs of building expensive high capacity transit. In addition, similar cities such as Dallas and Los Angeles have expanded upon their light rail systems only to see ridership decline [105].

Houston METRO already operates an extensive Park & Ride system, but the ridership is dismal (3%) because the service is neither fast nor frequent [64] [106]. Traditional rail and buses may not provide the answer to Houston's public transportation problem. This chapter explores the idea of an autonomous system to transport commuters from the suburbs to central Houston.

4.2 Demand

The annual average daily traffic (AADT) of the six highways with HOV lanes was found to be 1.6 million vehicles each day [107]. It was assumed that 10% of the vehicles travel during the design hour (explained in Section 4.4.1), the design hour traffic is 1.5x the average peak hour traffic, and the AM peak is spread out over 3.5 hours. These assumptions yielded a daily AM demand of 370,000 riders.

4.3 Existing Transport Options

4.3.1 Park & Ride

28 Park & Ride (P&R) lines transport commuters from suburban neighborhoods to the perimeter of downtown [24]. An example P&R bus is shown in Figure 4.2.

Fig. 4.2 Park & Ride Vehicle [108]

Commuters drive from their homes to nearby P&R lots, board a bus, and are driven via the High Occupancy Vehicle (HOV) lanes on the highway to transit centers in central Houston [24]. The locations for the different P&R stations are shown in Figure 4.3.

Fig. 4.3 Map of Park & Ride Locations [24]

The average weekday daily ridership for commuters on the P&R lines is 31,000 single boardings each day [64]. Ridership is declining, down 1% this year [64]. The P&R fares vary between \$2 and \$4.50 depending on the location [24]. The weighted average cost per ride was calculated to be \$3.84 [24] [64]. The map in Figure 4.3 is color-coated based on the price of the ride, described in Table 4.1.

Table 4.1 Park & Ride Single Fares [24]

Blue	Yellow	Red	Green	Weighted Average
\$2.00	\$3.25	\$3.75	\$4.50	\$3.84

HOV Lanes

The P&R Vehicles travel on the HOV lanes of Houston's highways, barrier-separated lanes open to buses, vanpools, or carpools [109]. The HOV lanes incorporate direct access ramps to P&R lots or transit centers, segregated from regular traffic, presented in Figure 4.4 [110].

Fig. 4.4 Direct Access Ramp from HOV Lane to Park Ride Facility [110]

There are 155 miles of HOV lanes on the 6 major highways that flow into Houston, depicted in Figure 4.5 [111].

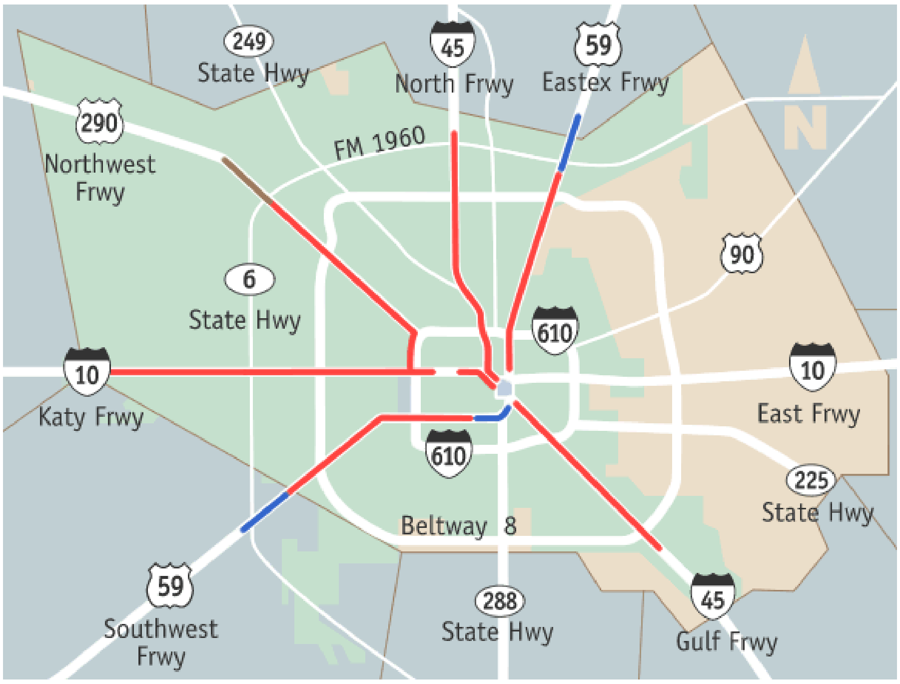

Fig. 4.5 Map of HOV Lanes [111]

The advantage to the HOV lanes is that traffic moves much faster because they are far less congested than the non-HOV highway lanes. The average speed of a vehicle on the HOV lane is 50-55 mph as opposed to 24 mph on non-HOV lanes during peak hours [111]. 15 of the 28 P&R stations lie along the HOV lanes, named in Table 4.2 [24].

Table 4.2 P&R Stations Along HOV Lanes [24]

Highway Name	P&R Station Names		
I-45 North	Spring	Kuykendahll	
US 59 North	Townsend	Eastex	
US 59 South	Westwood	West Bellfort	
I-45 South	El Dorado	Fuqua	Monroe
I-10 West	Addicks	Grand Parkway	Kingsland
US 290 West	Cypress	Northwest Station	West Little York

Houston is poised to be the leader in deploying autonomous bus systems because it already has the necessary infrastructure: barrier-separated HOV lanes that can segregate autonomous buses from regular traffic. This would make the testing deployable in the near-term, safer, and subject to public approval. Houston's transportation experts agree that the earliest deployment of level 4 autonomous vehicles will be in the form of buses on the HOV lanes [6].

4.4 Performance and Service Level Targets

4.4.1 Capacity

The peak system capacity reflects the peak demand on an average day. The k-factor in transport engineering is defined as the "proportion of AADT occurring in the peak hour" [67]. Multiplying the k-factor by the AADT gives the design hour volume (DHV) [67].

$$DHV = kfactor \times AADT$$

The k factor differs throughout the year. For example, the busiest peak hour of the year corresponds to the highest k-factor. The transportation system should not be designed to accommodate the busiest peak hour of the year because then it would be underutilized for the other 364 days of the year. The system also should not be designed for the least busy days because then it would not have adequate capacity. For this, k-30 (the 30th highest hourly volume of the year) is usually used to find the DHV [67]. k-30 ranges from 7-12% in the United States, so the value of 10% was used as the k-value to find the DHV [67]. The average occupancy per vehicle differs for each highway, found in Table 4.3.

Table 4.3 Average Occupancy of Vehicles on Houston Highways [109]

Highway Name	Average Vehicle Occupancy
I-45 North	1.02
US 59 North	1.05
US 59 South	1.07
I-45 South	1.07
I-10 West	1.12
US 290 West	1.05

The average occupancy per vehicle was multiplied by the DHV to get the peak passenger transfer of the highways, presented in Figure 4.6.

$$Peak\ passenger\ transfer = Average\ occupancy\ factor \times DHV$$

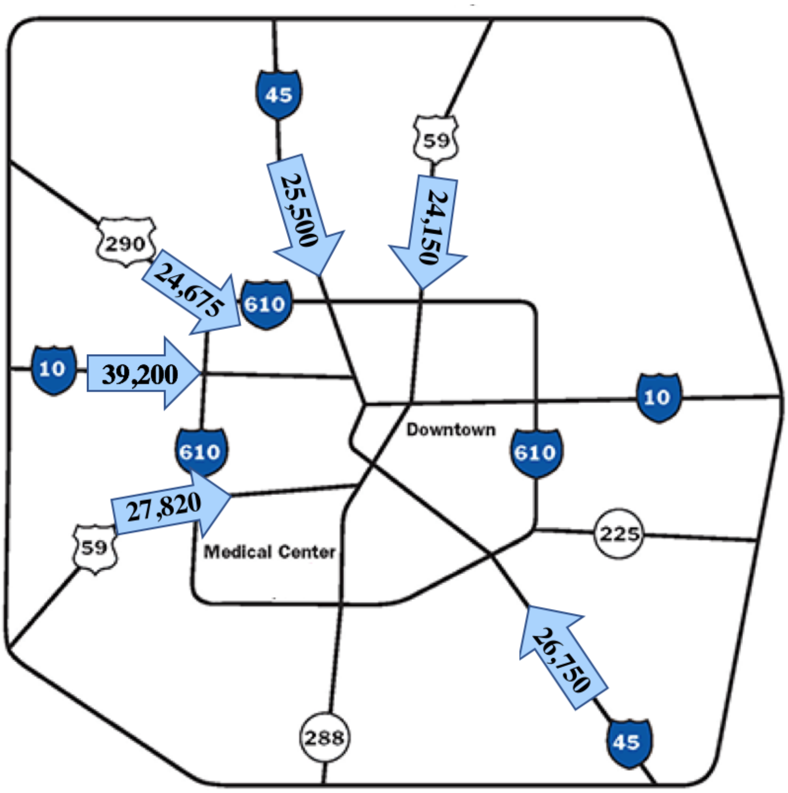

Fig. 4.6 Design Hour Inbound Passenger Flow [112]

The ridership for the 15 P&R stations that lie along HOV lanes is 10,000 riders per day, amounting to 3% of commuters [64] [107]. A 20-30% mode shift is typical when introducing a new inbound system, so it was assumed that the new system would transport 28% of inbound commuters. Thus, the system was designed to accommodate this number of commuters (47,000), known as the design hour pph.

$$Design\ hour\ pph = Peak\ passenger\ transfer \times 28\%$$

4.4.2 Journey Time

The distance between each P&R and Downtown was found. The MicroMetro vehicles (described in Section 4.6.1) are capable at traveling at 99 mph [113]. It was assumed that the HOV lanes would be blocked off for the exclusive use of the MicroMetros; the high MicroMetro speeds are due to the fact that these vehicles would be separated from normal traffic. They also could platoon and travel even faster. Taking into account the current speed limit of 70 mph on Texas' highways, it was conservatively estimated that the MicroMetro travels at an average speed of 60 mph to take into account time spent traveling from the P&R lots to the highway [114]. This speed and the distance were used to find the journey time.

The journey time could decrease if the speed limit increases. The Texas Transportation Commission can set a speed limit of up to 85 mph if that speed is deemed safe after a traffic engineering study [114].

The weighted average in-vehicle journey times across all 15 routes for a car, the P&R system, and the MicroMetro traveling at 60mph, 85mph, and 99mph are presented in the Appendix in Table C.1 and in Figure 4.7.

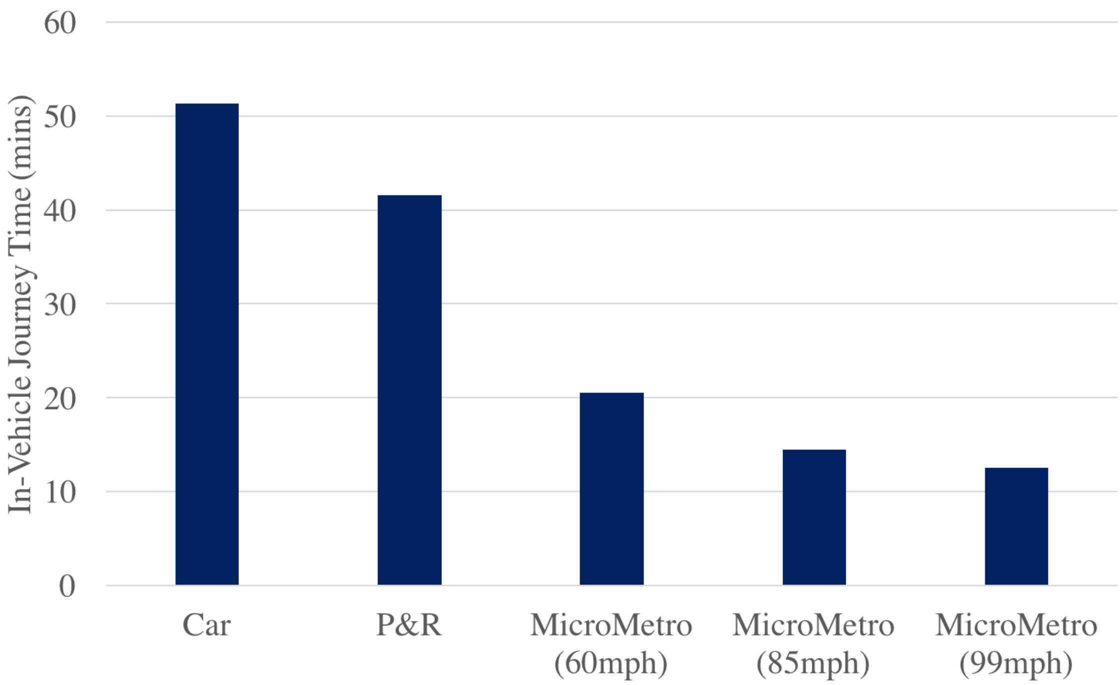

Fig. 4.7 Weighted Average Car, P&R, and MicroMetro In-Vehicle Single Journey Times [109] [59] [24]

Even using the conservative estimate of an average speed of 60mph for the MicroMetro yielded an average travel time 51% shorter than the current P&R travel times, meaning that the MicroMetro system would indeed provide faster services [24].

4.4.3 Frequency

Certain highways host multiple different P&R routes, as described in Table 4.2. The number of riders on a specific P&R route as a percentage of total P&R riders on that highway was found [64]. This was then used to find the number of MicroMetro riders for each particular line, which in turn was used to find the frequency, expressed in Table C.2 in the Appendix.

$$Vehicle\ departures\ per\ hour = \frac{Number\ of\ MicroMetro\ riders\ per\ line}{Capacity\ of\ MicroMetro}$$

The weighted average frequency of the MicroMetro system would be 1 minute, less than the P&R frequency of 8 minutes. The total journey time; including end-to-end in-vehicle time, the maximum waiting time, and walking time; is shown in Figure 4.8.

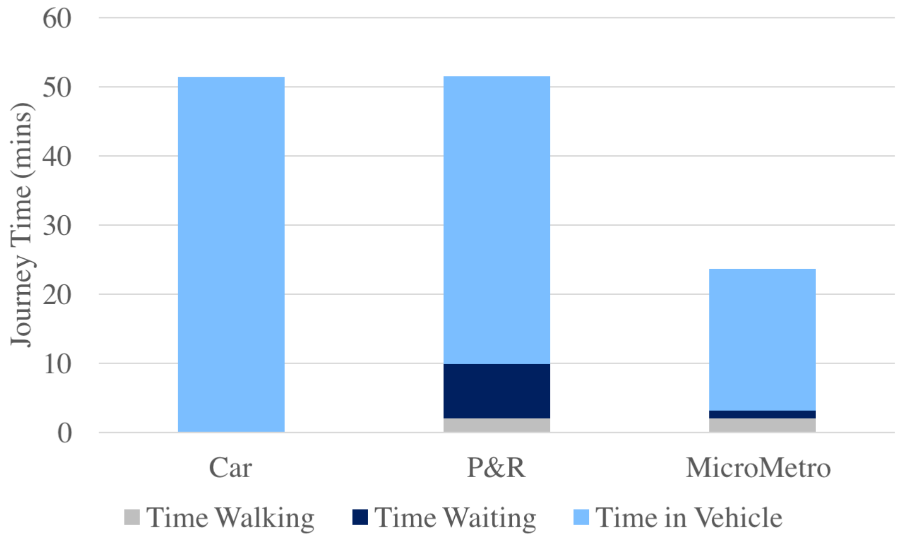

Fig. 4.8 Single Journey Time Including Maximum Wait, End-to-end In-Vehicle Time, and Maximum Walking Time Comparison by Mode

4.5 Routes and Infrastructure

4.5.1 Routes

It was assumed that the current P&R routes were deliberately chosen to accommodate the high-demand routes for commuters. For this, the P&R routes that utilize HOV lanes were chosen to be the MicroMetro routes. These routes initiate in suburban neighborhoods and end at the perimeter of Downtown. The P&R routes are illustrated in Figure 4.9.

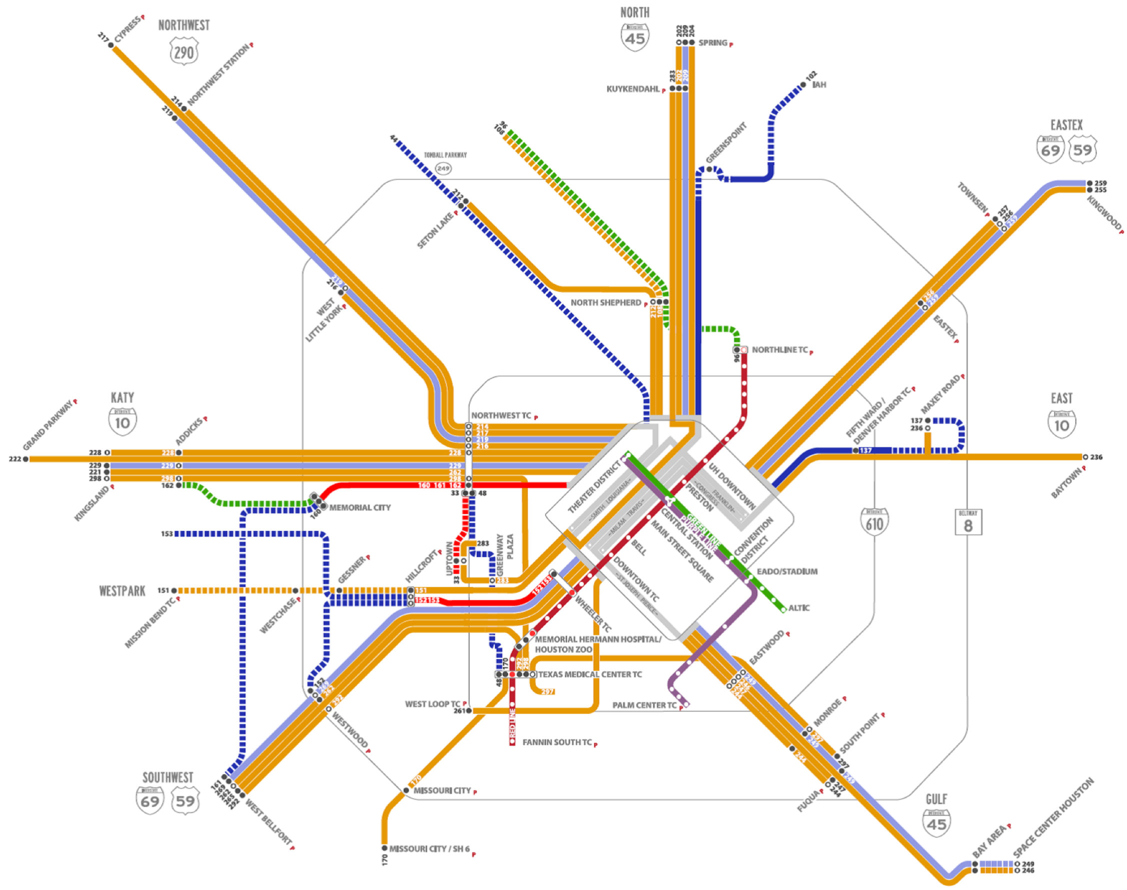

Fig. 4.9 Map of Park & Ride Routes [64]

4.5.2 Infrastructure

The HOV lanes are 5.94 meters wide, wide enough to fit the MicroMetro system [111]. An illustration of an HOV lane adapted to accommodate the MicroMetro system is depicted in Figure 4.10 with the dimensions marked in millimeters. This figure shows two lanes for vehicles travelling bidirectionally, an emergency walkway, and a concrete barrier.

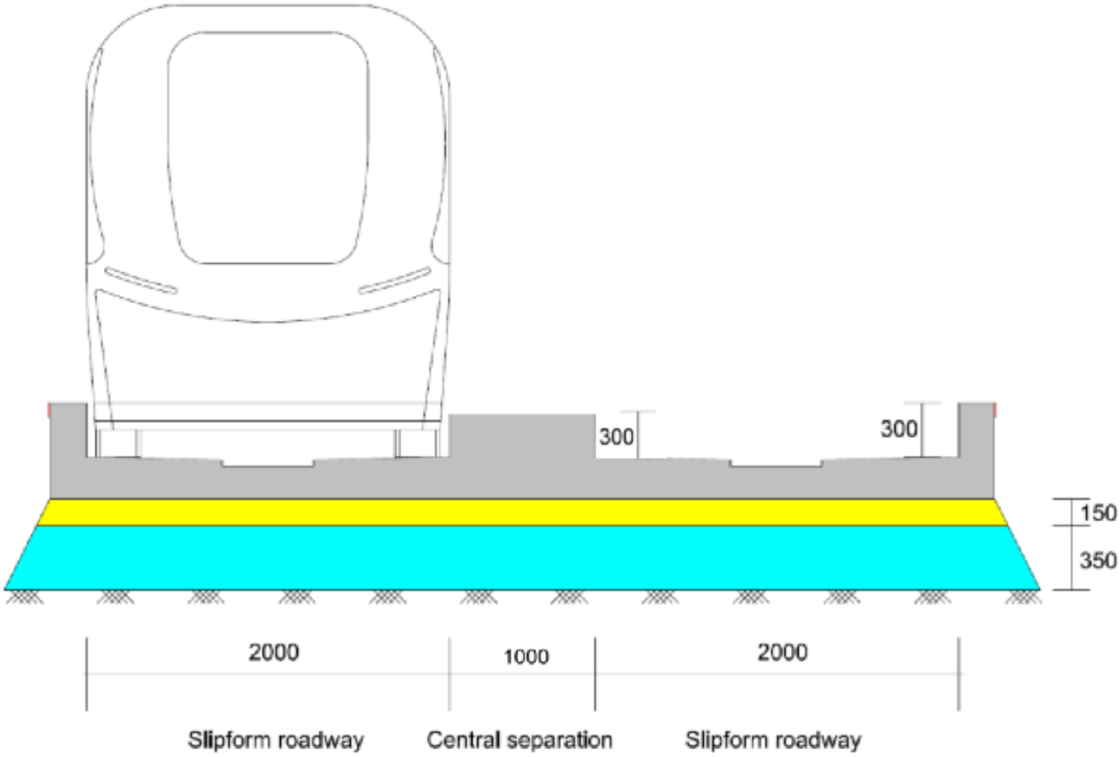

Fig. 4.10 MicroMetro Crossection with Dimensions in Millimeters [113]

The current HOV lanes run inbound to central Houston in the morning and outbound to the suburbs in the afternoon [111]. The MetroNext Plan calls for reverse commute options and two-way P&Rs [25]. The MicroMentro vehicles are narrow enough that the HOV lanes could be bidirectional, thus satisfying these requests.

The middle concrete wall provides a non-intrusive way to prevent crashes between vehicles. It is tall enough to prevent the wheels from jumping between lanes, but short enough to be used as an elevated emergency walkway.

Terminus stations would be located where each of the 6 highways feed into Downtown and at the start of each of the 15 routes. This amounts to 21 total terminus stations at grade (on the street level). The terminus stations would include charging infrastructure.

There are existing surface lots currently used by the P&R system. In addition, the HOV lanes are already barrier-separated. This existing infrastructure avoids the need for the costs of paving new lots or building a lane safe for autonomous buses. The infrastructure costs of a pathway at grade is $5M per two-way km, amounting to a total of $1.42B if Houston were to build brand new barrier-separated pathways for the MicroMetro system [113]. Building this system on the HOV lanes avoids the majority of these infrastructure costs, therefore saving a billion dollars, making Houston the ideal candidate for building this system. The emergency walkways and pathway lighting would still need to be built on the HOV lanes.

4.6 Vehicle Fleet

4.6.1 Vehicle Size

Transporting commuters from the suburbs to central Houston represents a long-distance, fixed-route, direct commute. For this, a large vehicle is needed. The vehicle chosen is the MicroMetro, a 60-passenger mass transit vehicle proposed for use in Milton Keynes, shown in Figure 4.11 [113]. The MicroMetro was designed with the aim of "serving the high-volume, fixed route demands which are primarily defined by commuters," [113]. This goal applies to Houston's transit needs.

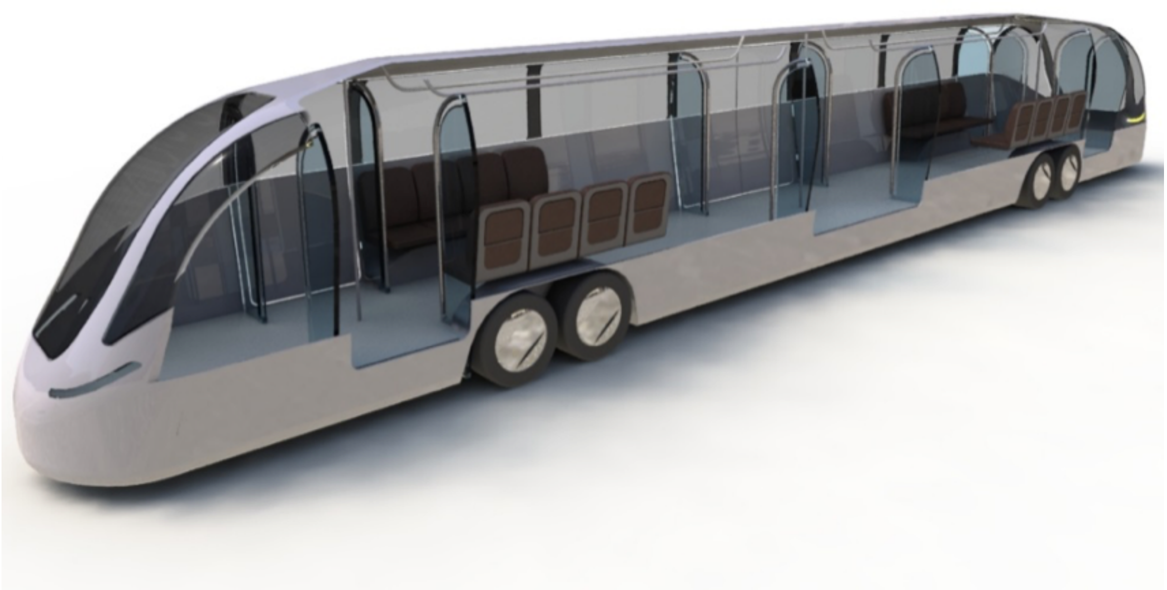

Fig. 4.11 MicroMetro Vehicle [113]

4.6.2 Number of Vehicles

The energy requirement for each of the 15 routes was calculated using the distance of the route and the energy requirement of the MicroMetro (2.35 kWh/km) [113]. Using the charge rate of the MicroMetro (350 kW), the amount of time needed for charging was calculated. It was assumed that it would take 5 minutes to load and unload the vehicles. The round trip journey time, charging time, and loading and unloading time were then used to find the total round trip journey time. The average round trip journey time was 67 minutes. The number of vehicles needed for each route was found by dividing the round trip journey time by the frequency of the vehicles. This gave an aggregated fleet size of 900 MicroMetros.

$$Number\ of\ vehicles\ needed = \frac{Round\ trip\ journey\ time}{Frequency}$$

4.7 Economics

Vehicles

The aggregated fleet size of 900 MicroMetros was found in Section 4.6.2. Each MicroMetro would have an upfront cost of $600,000, assumed to be paid back over a period of 10 years at a 4% interest rate [113]. The annual cost of vehicles would be $65,607,000.

Infrastructure

Each of the 21 terminus stations at grade would cost $3,780,000 [113]. The emergency walkways and pathway lighting would cost $195,000/km [113]. The infrastructure costs were assumed to be paid back over 10 years at a 4% interest rate. The annual cost of infrastructure would be $16,375,000.

Fuel Consumption

The Micrometro operation hours were derived from the P&R hours. It was assumed that the P&R buses run most frequently when the demand is the highest. The P&Rs are most frequent between 5-8:30 AM and 3:30-6 PM [24]. For this, a 3.5 hour peak was assumed for the morning and a 2.5 hour peak for the afternoon. The MicroMetro system was assumed to only run during the morning and afternoon peaks. The total kilometers per day that all the vehicles would travel was calculated. The MicroMetros would require 2 kWh/km of electricity and 30 kW of cooling power, which translates to 2.45 kWh/km [113]. Multiplying this by the total kilometers driven in a day gave the daily electricity consumption which was then used to find the annual electricity consumption.

$$Annual\ fuel\ consumption = 2.45 kWh/km \times total\ daily\ km \times 7\ days/week \times 52\ weeks/year$$

The average price of electricity used for the transport sector in Texas over the past year, 7.44¢/kWh, was multiplied by the annual electricity consumption to give the annual cost of fuel consumption, \$13,210,000.

$$Annual\ cost\ of\ fuel\ consumption = Average\ price\ of\ fuel \times Annual\ fuel\ consumption$$

Staff

The remote operators were assumed to be responsible for watching 5 vehicles at a time. At all times, it was assumed that the remote operators also needed a shift manager and secretary requiring office space. In addition, it was assumed that one mechanic was needed per every 10 vehicles running. Every employee (remote operators, secretaries, shift managers, and mechanics) were assumed to make \$35,000 per year. The annual cost of staff would be \$10,381,000.

4.7.1 Summary of Costs

The breakeven cost per single ride was found by assuming that the MicroMetro system would capture 28% of commuters each day.

Table 4.4 Summary of MicroMetro Costs

Cost Description	Cost
Vehicles	\$65,607,000
Infrastructure	\$16,375,000
Fuel Consumption	\$13,210,000
Staff	\$10,381,000
Total Annual Costs	\$105,573,000
Breakeven Cost Per Ride	\$2.01

4.7.2 Sensitivity Analysis

Different inputs to the model were varied to determine the effect on the annual price of the MicroMetro system and the breakeven cost per single ride. The inputs varied were interest rate, upfront vehicle cost, electricity price, and ratio of remote operators to vehicles.The high, medium, and low estimates for each input are summarized in Table 4.5. Effects of the varied inputs on specific costs components are found in Appendix C.

Table 4.5 Low, Medium, and High Estimates for Sensitivity Study Inputs

Input	Low Estimate	Medium Estimate	High Estimate
Vehicles	$300,000	$600,000	$900,000
Interest Rate	4%	6%	8%
Electricity Price	6.25 ¢/kWh	7.44 ¢/kWh	8.46 ¢/kWh
Remote Operators:Vehicle Ratio	1:5	1:20	1:50

The effects of the sensitivity study on the annual cost of the system and the breakeven cost per single ride are illustrated in Figure 4.12 where each variation is compared to the baseline case.

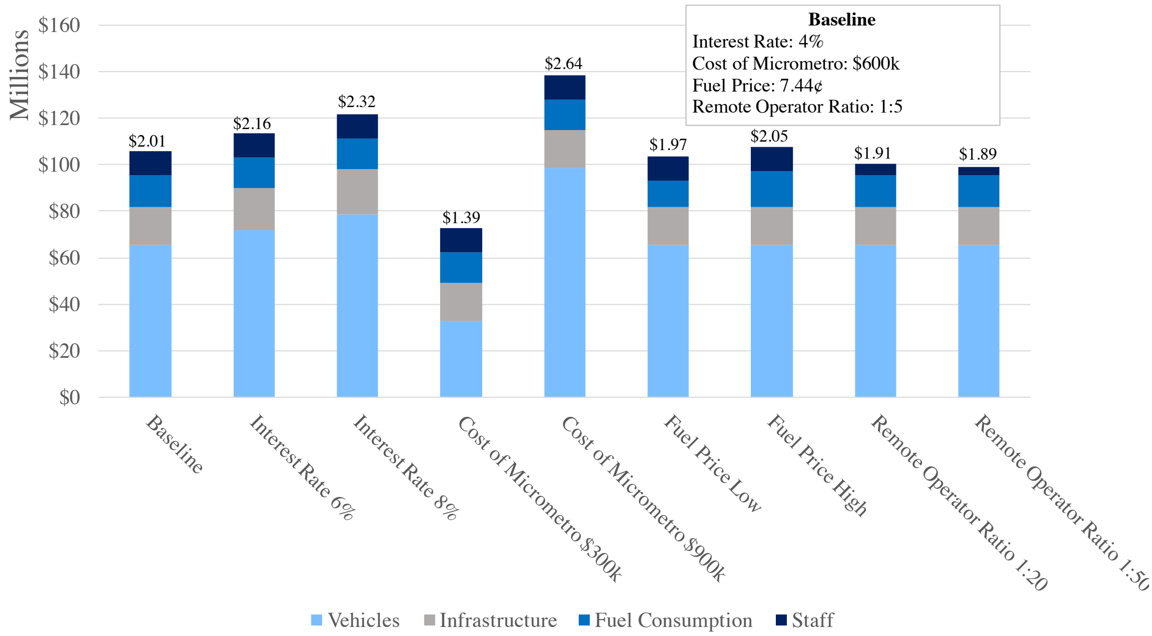

Fig. 4.12 Economics Sensitivity Analysis with Cost Breakdown by Component and Breakeven Cost per Single Ride

The input with the biggest impact is cost of the vehicle because the cost of vehicles is the biggest component cost of the system. Therefore, changing the cost of vehicles largely impacts the total annual costs.

4.7.3 Economics Comparison

Park & Ride

The cost comparison of the MicroMetro and P&R systems is shown in Figure 4.13.

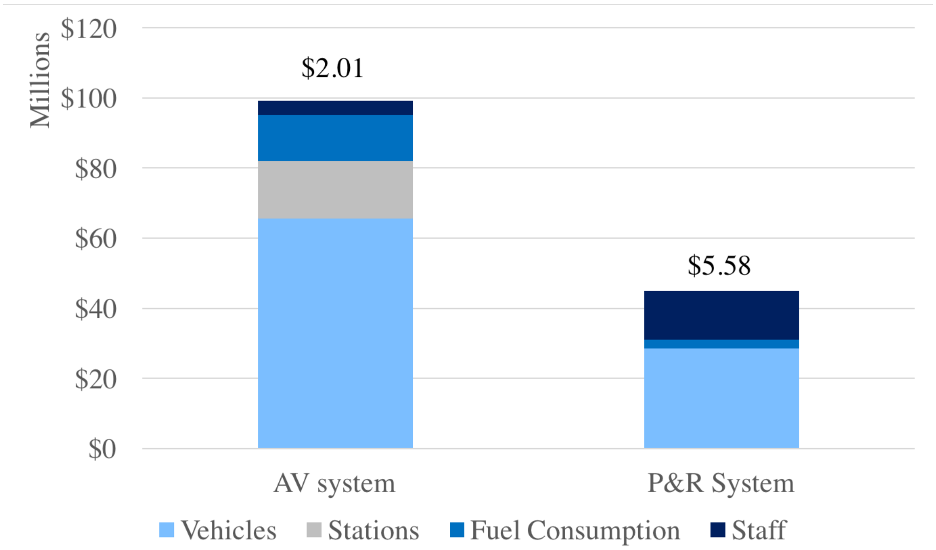

Fig. 4.13 Annual Cost Comparison of MicroMetro and P&R System with Breakeven Cost per Single Ride [64] [69] [115]

The MicroMetro system would cost more than the P&R system because it would need more vehicles, new infrastructure, and more fuel because there would be more kilometers driven. The MicroMetro system would have a lower breakeven cost per ride because it was assumed to capture more riders (28% of commuters compared to the 3% that the P&R system services) [64].

The autonomous system would need to exceed 10% ridership levels to have a cheaper breakeven cost per single ride than the P&R system, shown in Figure 4.14.

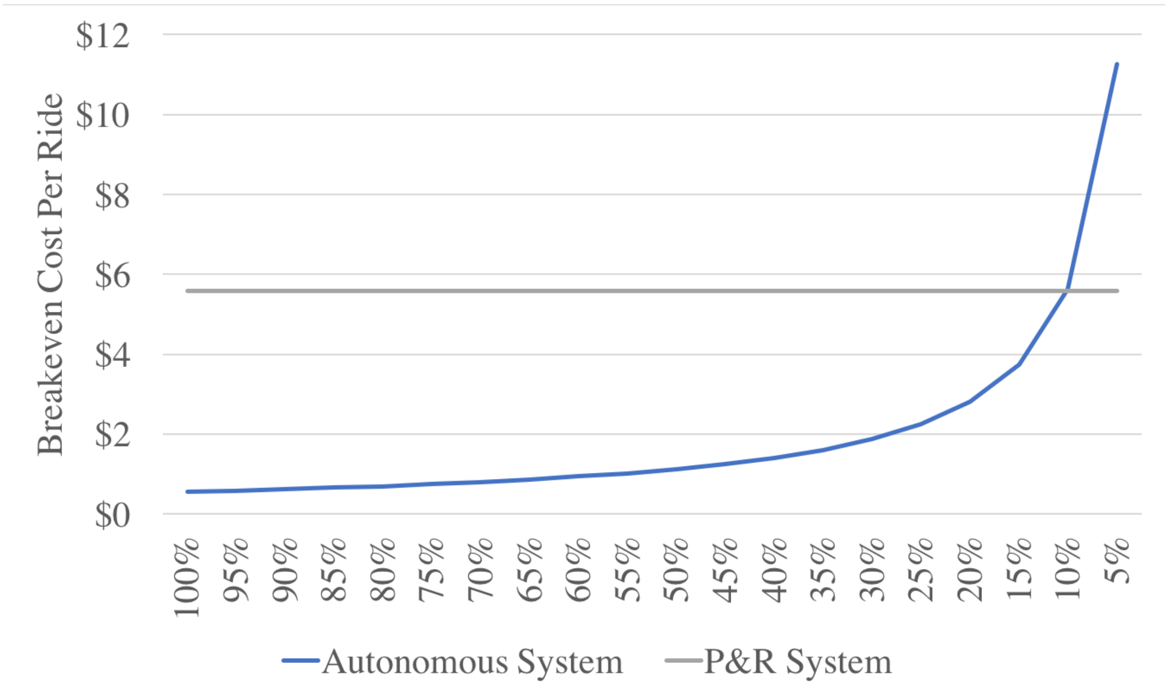

Fig. 4.14 Breakeven Cost Per Single Ride vs. Assumed Ridership Level with Breakeven Cost per Single Ride of P&R System

Car

The different inputs used to find the daily cost of driving ($10.38) are shown in Table 4.6.

Table 4.6 Average Daily Cost of Driving [59] [14] [115] [98] [62]

Inputs	
Weighted Average Distance from Suburbs to Central Houston	20.5 miles
Average American Fuel Economy	22 mpg
Gallons of Gas Used per Single Trip	.93
Gas Price	$2.69
Single Trip Gas Costs	$2.51
Average Daily Price of Parking	$5.36
Round Trip Gas and Parking Costs	$10.38

These costs include only the cost of fuel consumption and parking, excluding the costs of buying and maintaining a vehicle.

4.7.4 Financial Viability

The assumptions used to calculate the financial viability of the Downtown system are summarized in Table 4.7.

Table 4.7 Assumed Final Ridership Level, Fare, and Growth Rate

Final Ridership Level	Fare	Growth Rate	Time Period
28%	$3.84	year 1: 50% final ridership year 2: 80% final ridership year 3+: 100% final ridership	10 years

The costs, revenues, profits, and cumulative profits for each year over a period of 10 years are presented in Table C.7 in the Appendix. Figure 4.15 shows the cumulative profits over the 10 year period. This graph presents the initial capital outlay ($675 million) as the first point of the graph, the payback period (62 months) as the point where the graph crosses the x-axis, and cumulative profits after the 10 year period ($836 million) as the end point of the graph.

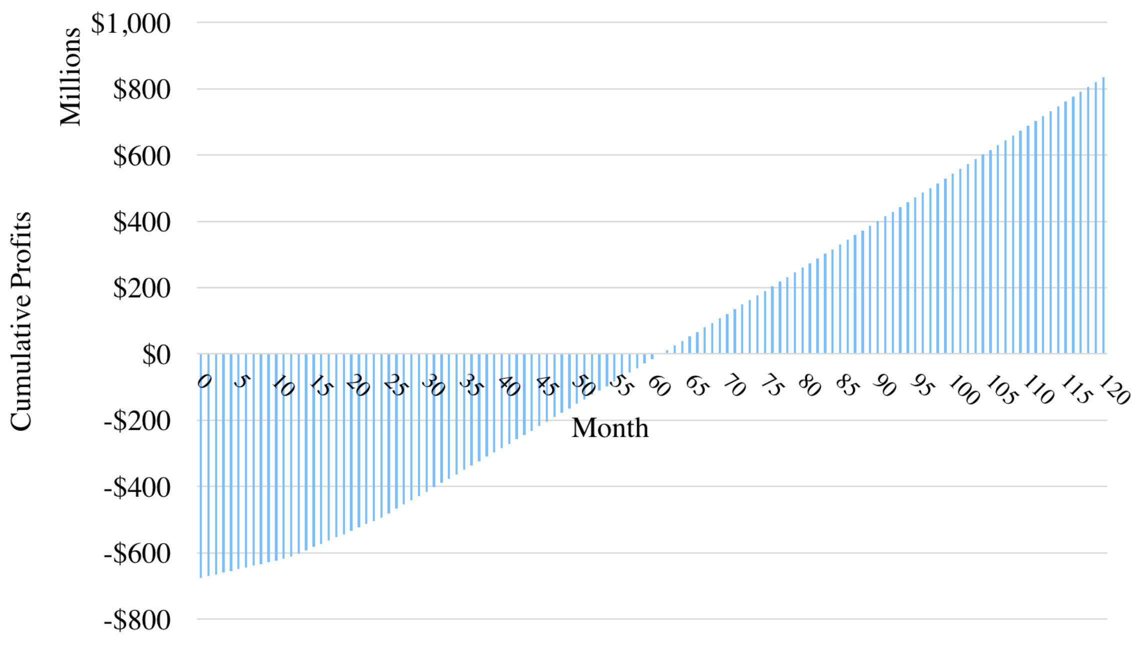

Fig. 4.15 Cumulative Profits of MicroMetro System Over 10 Year Period with $3.84 Fare, 28% Final Ridership, and 3 Years to Reach Final Ridership Level

The ROCE over the 10 year period is presented in Figure 4.16.

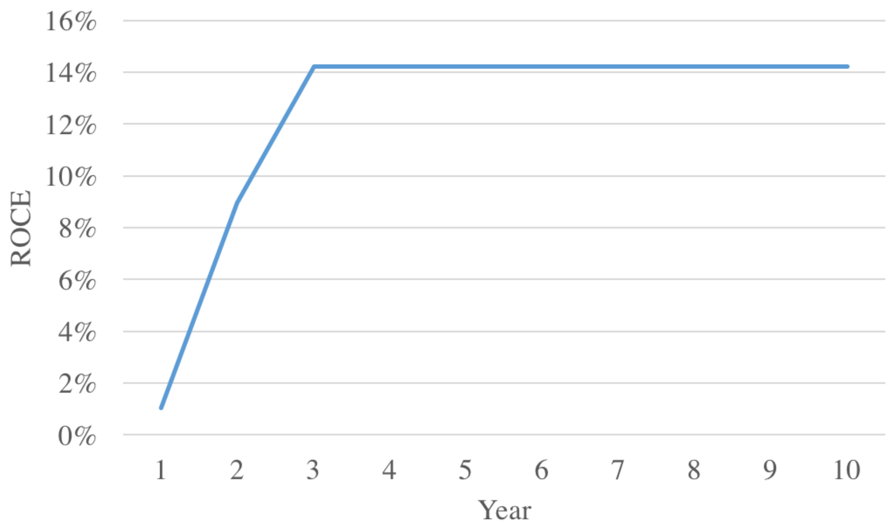

Fig. 4.16 ROCE of AV System Over 10 Year Period with $3.84 Fare, 28% Final Ridership, and 3 Years to Reach Final Ridership Level

The ROCE stabilizes at 14%, higher than the average ROCE value for non-financial corporations in the UK (12%) [75]. Therefore, the proposed system would use capital to generate profits more efficiently than the average UK company.

4.7.5 Sensitivity Analysis

The fare price, ending ridership level, and ridership growth were varied and the effects illustrated in Figures 4.17 and 4.18.

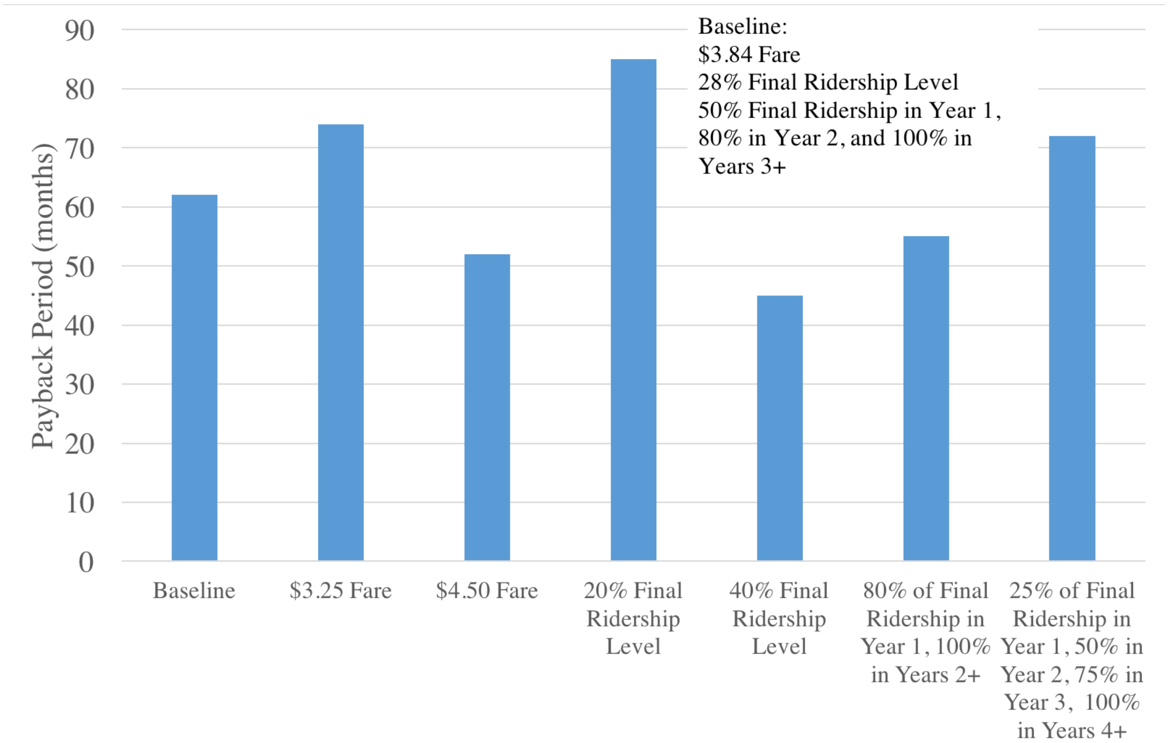

Fig. 4.17 Payback Period Sensitivity Analysis Baseline, Varied Fare, Varied Final Ridership Level, and Varied Ridership Growth

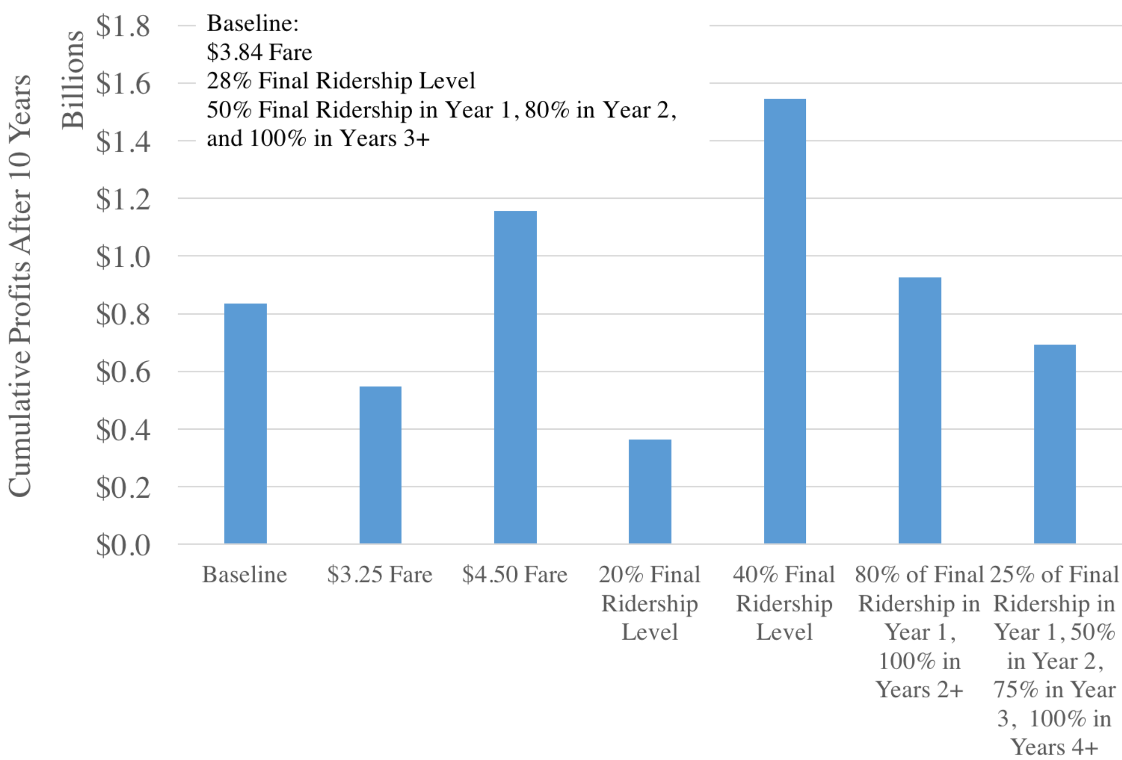

Fig. 4.18 Cumulative Profits After 10 Years Sensitivity Analysis Baseline, Varied Fare, Varied Final Ridership Level, and Varied Ridership Growth

The final ridership level has the largest effect on the profitability of the system.

Fare Price

The threshold for the system to be profitable yielded a breakeven fare price of $2.13. The current P&R system prices range from $2.00 to $4.50 depending on location, as presented in Table 4.1. The cheapest P&R fare is lower than the breakeven threshold; setting the fare at that low price means that the system operator would never break even and therefore would rely on public subsidy or other financing mechanisms. The system was assumed to be priced the same as the weighted average current P&R system fare ($3.84), but it could be priced lower at the second lowest current P&R fare ($3.25) to compete with the existing transit or priced higher at the current highest P&R fare ($4.50) to make the system more profitable [60].

Final Ridership Level

The threshold for the system to be profitable is 14% ridership, which is much higher than the 3% ridership level of the existing P&R system [106] [64]. This would require capturing

52,000 new riders, a very ambitious goal. The final ridership level was varied between 20% and 40% for the sensitivity analysis.

Ridership Growth

For the baseline scenario, it is assumed 50% of final ridership numbers for year 1, 80% for year 2, and then 100% for year 3 and onwards. A more optimistic scenario assumed faster uptake in ridership with 80% of final ridership numbers for year 1 and 100% for year 2 onwards. A less optimistic scenario assumed a slower uptake in ridership with 25% of final ridership numbers for year 1, 50% for year 2, 75% for year 3, and 100% for year 4 onwards.

This financial analysis suggests that the MicroMetro system has the potential to be self-financing via farebox revenues over a 10-year loan period if it surpasses a $2.13 fare price or 14% final ridership levels.

4.8 Emissions

The inputs and resulting MicroMetro, car, and P&R emissions are presented in Tables 4.8, 4.9, and 4.10.

Table 4.8 MicroMetro Emissions [113] [76]

Inputs	
MicroMetro Energy Requirement	2.45 kWh/km
Texas Electricity Supply Carbon Intensity	476 gCO_2e/kWh
MicroMetro Carbon Intensity (per vehicle km)	1,119 gCO_2e
Occupancy Factor	75%
MicroMetro Carbon Intensity (per passenger km)	25 gCO_2e

Table 4.9 Car Emissions [14] [109]

Inputs	
Average Car Fuel Economy	22 mpg
Gasoline Emissions	8,887 gCO_2e/gallon
Vehicle Occupancy	1.07
Car Carbon Intensity	236 gCO_2e/passenger km

Table 4.10 P&R Emissions [69] [80] [64]

Inputs	
P&R Capacity	55 passengers
Vehicle Emissions	1,323 gCO_2e/vehicle km
Vehicle Occupancy Factor	38%
P&R Carbon Intensity	63 gCO_2e/passenger km

As the energy supply transitions to low-carbon sources, the emissions per kWh of electricity generated would decrease. Taking Vermont's current electricity breakdown would yield 1gCO_2e/passenger km [77]. The emissions comparison for the different modes is shown in Figure 4.19 where the autonomous system has the lowest emissions per passenger kilometer.

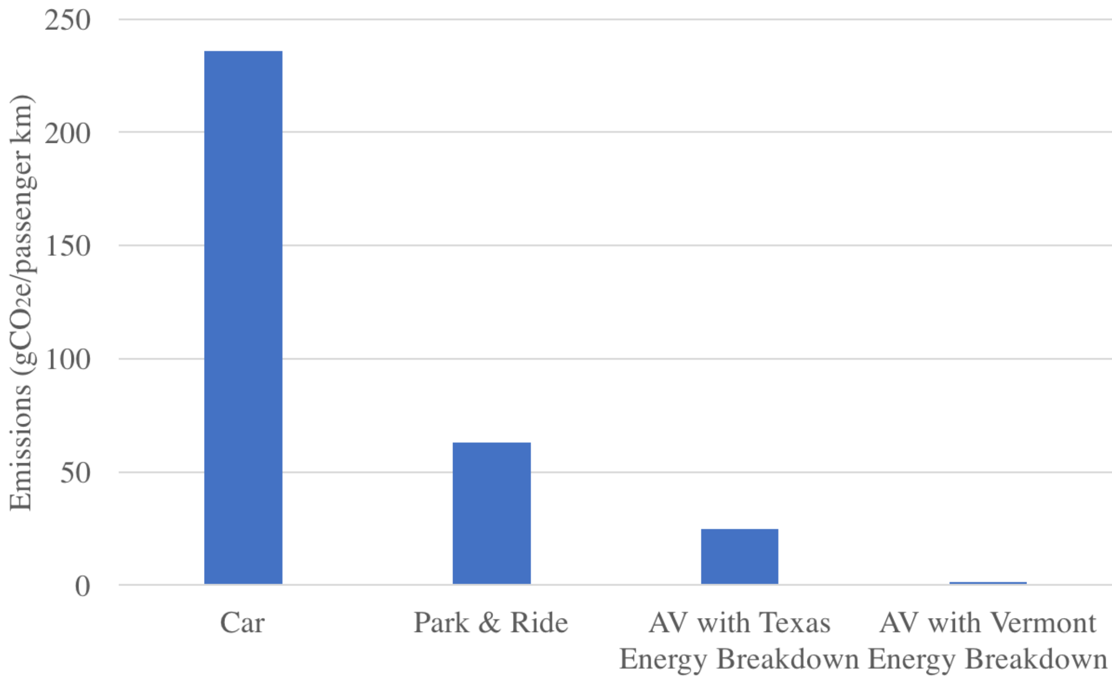

Fig. 4.19 Emissions Comparison by Mode

Chapter 5

First Mile

5.1 Overview

The initial portion of the journey, transporting the commuter from their home to their neighborhood transit center, is generally dubbed the "first mile." The first mile problem in the case of Houston suburbs is location-dependent. This chapter will describe the varied solutions to the different first-mile cases for generalized Houston neighborhoods. This chapter will not follow the analytical steps that make up the methodology in other chapters because the neighborhoods are too varied to describe a one-size-fits-all approach. Instead, the different possibilities will be described superficially.

The use of autonomous vehicles for the first mile of the journey is still far-off in the future. Segregated autonomous vehicles are already being tested, while integrated autonomous vehicles are at least 6 years away [50]. The other sections describe AV systems that can be segregated from normal traffic: TMC shuttles would follow barrier-segregated lanes, Downtown would be open for the exclusive use of autonomous pods, and the MicroMetro system would run on the barrier-separated HOV lane. The first mile vehicles have no realistic path for segregation. Infrastructure for segregated lanes would be too expensive for the limited use (short distances and a small fraction of people) and it is impossible to close all streets to regular traffic because people must be able to drive within their neighborhoods.

The integrated public transit system should not be held up by the fact that autonomous vehicles are not currently capable of integration with normal road traffic and therefore not ready for the first-mile application. Instead, different solutions can be applied to the first-mile problem so that Houston commuters have a transit solution that serves their entire journey, door-to-door. The three strategies that will be discussed are demand-responsive shuttles, ride-sharing, and driving to the local P&R.

5.2 Large Neighborhoods

Large neighborhood can take the approach of demand-responsive shuttle systems. The system is an anywhere-to-one system, meaning that commuters come from many different neighborhoods or streets to converge upon the one MicroMetro that leaves from their city. The solution could be a fixed-route shuttle that stops at different street corners around the neighborhood before dropping commuters off at the transit center. A better system would be a demand-respsonsive shuttle that stops at street corners only when there is a passenger to pick up.

5.2.1 Example: Sugar Land

Sugar Land is a city in Fort Bend County, Texas that lies 16 miles from central Houston [59]. Sugar Land's population is 88,000 inhabitants spread out over 35 mi^2[116]. This means that the population density is 2,600 inhabitants per mi^2.

Sugar Land is a commuter town to Houston. It lies on US 59 South so that commuters can conveniently take the highway into Houston [59]. Fort Bend County is made up of 766,000 people, so Sugar Land accounts for 12% of Fort Bend County's population [117]. 182,000 people commute from Fort Bend County to Harris County, which encompasses central Houston, for work each day [118]. Assuming an even distribution of commuters throughout Ford Bend County, 21,000 people commute from Sugar Land to Harris County each day for work. Assuming that 28% of these people use the MicroMetro system, 6,000 people need to get from their homes to the MicroMetro. This gives a design hour pph of 2,500. But these people are spread out across Sugar Land, which means that 73 people per mi^2 need a ride in the design hour. This is dense enough to call for a shuttle, but not dense enough to have a major transportation system in place.

5.3 Small Neighborhoods

Small neighborhoods can take the approach of ride-sharing or individuals driving to their neighborhood transit center and parking their cars at the local P&R. Ride-sharing would occur if the neighborhoods are densely populated. Individuals would drive to the local P&R if their neighborhood has rural characteristics and is too sparsely populated for a ride-sharing system to be justified. Though this means that individuals in those neighborhoods cannot abandon car ownership altogether, they would have improved access to public transit.

5.3.1 Example: Nassau Bay

Nassau Bay is a densely populated neighborhood near the Johnson Space Center with a population of approximately 4,000 inhabitants spread out over 1.7 miles squared [119]. This leads to a population density of 2,300 inhabitants per mi^2, which is similar to the density of Sugar Land [120]. Nassau Bay is very close to the El Dorado P&R [59]. 54% of the population works [119]. Assuming that half of these employees commute to central Houston for work and 28% of them take the MicroMetro means that 300 people take the MicroMetro from Nassau Bay to central Houston each day. Assuming these people are evenly distributed across Nassau Bay and travel during a 3 hour morning peak means that on average 60 people per mi^2 take the MicroMetro system per hour. In this case, traditional ridesharing is justified because of the commuter density. Investing in an AV system would not be justified because of the low demand.

5.3.2 Example: Thompsons

Thompsons is a town in Fort Bend County with a population of 300 inhabitants spread out over 22 km^2 [121]. This leads to a population density of 40 people per square mile, the lowest in the Houston area [120]. Assuming that the working population of Fort Bend County is evenly distributed, 75 people would travel from Thompsons to central Houston for work each day [118]. This is equivalent to 1 pph/km^2 [121]. This is a low commuter density and therefore ride-sharing does not make sense. The commuters would drive their car to the local P&R.

Chapter 6

Sustainability Evaluation

6.1 Integrated Journey

The previous chapters have explored the potential for autonomous vehicles to deliver a higher standard of service with fewer emissions at affordable prices in key geographical areas of Houston that represent different segments of a commute. This chapter now tests the autonomous solution against the key sustainability measures of social, financial, and environmental performance by examining an entire, integrated journey.

The end-to-end journey integrates different systems for the first mile, transit to central Houston, and last mile portions of the journey. A typical commute would follow this pattern: the commuter drives from their home to the Park & Ride station closest to them, waits for the MicroMetro, rides in the MicroMetro that drops them off at the perimeter of Downtown Houston, waits for the pod, and rides in the pod to the front door of their workplace Downtown.

There are two alternatives to the autonomous system: driving a personal car or using current public transportation options. A car journey would mean that the driver gets in their car at their home, drives to their workplace parking lot, parks, and walks from the parking lot to their workplace. The current public transit journey would mean that the commuter drives to their neighborhood P&R lot, parks, walks to the P&R pickup spot, boards the P&R, rides to the perimeter of Downtown, walks to the light rail stop, takes the light rail to the stop nearest their office, and walks to their office.

6.2 Evaluation of Autonomous System

The considerations of a public transit system, set out in Section 1.1 and reproduced in Figure 6.1, should be used to evaluate the system.

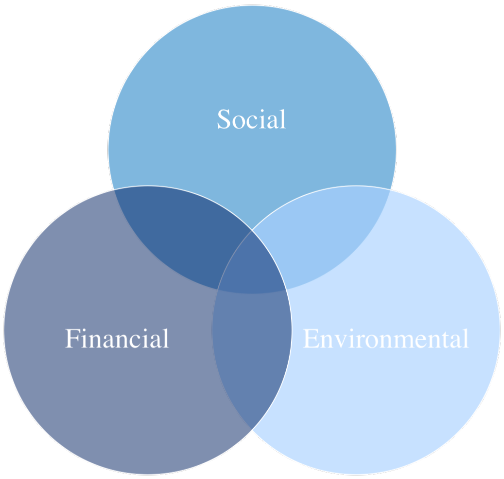

Fig. 6.1 Public Transit System Considerations

6.2.1 Social

The main social factor of this transit system is single trip journey time, including time spent waiting, riding, and walking. The single journey time comparison for all three systems is shown in Figure 6.2. The breakdown of the calculated and assumed times for each step of the journeys is found in the Appendix in Table D.1.

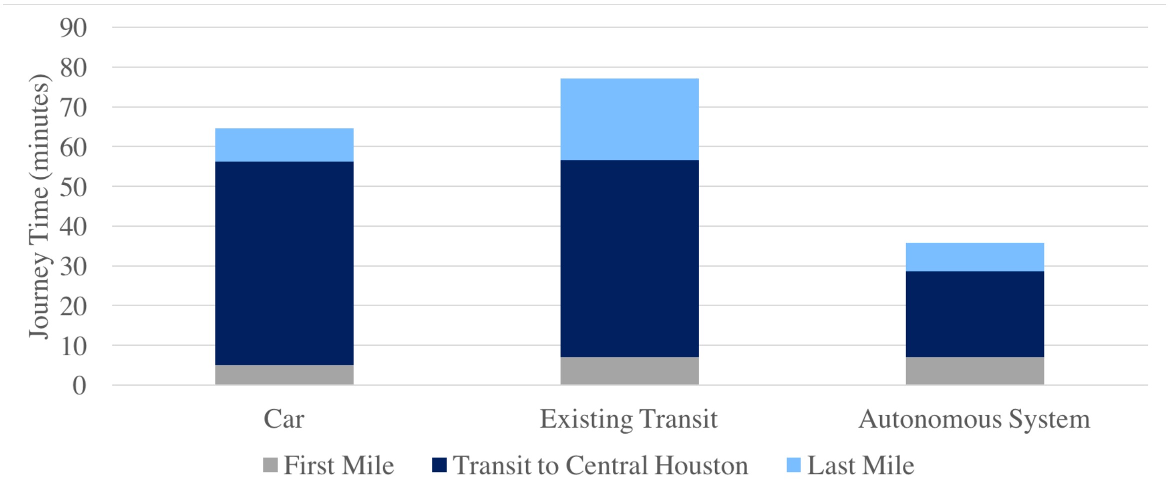

Fig. 6.2 Single Journey Time Including Maximum Wait, End-to-end In-Vehicle Time, and Maximum Walking Time Comparison by Mode

This dissertation suggests that an autonomous public transit system could provide a better quality of service than traditional forms of transit, such as bus and light rail systems. This is because the autonomous system could provide reduced journey times. Taking this system as opposed to driving would save commuters 58 minutes a day or 240 hours a year. The autonomous system could transform the transport landscape to support many smaller vehicles with more frequent departures, therefore cutting down waiting time. Also, segregation of AVs could lead to higher average speeds (as seen in the MicroMetro system), further reducing travel time. Lastly, the walking time could be reduced if the services are end-to-end, bringing commuters closer to the door of their workplace. Other social benefits of the autonomous system are improved road safety because human error in driving would be avoided, reduced congestion if this system encourages people to eschew private car travel for shared transit, improved access to transportation because it provides an end-to-end solution for commuters, more efficient use of space as less parking lots and garages would be needed, and more efficient use of time as commuters could work during their commute.

Despite all the possible social benefits of the autonomous system, there are also many drawbacks. A major drawback is that this system would require transfers between three vehicles for a typical commute. This is opposed to the dominant form of transport, driving, that requires no transfers. In addition, autonomous technology is new enough that it does not have the public's backing yet. It will need to be proven safe. Another social con is that access to Downtown would be restricted to AVs only and the MicroMetro system would require the exclusive use of the HOV lane for AVs. This could lead to pushback from people wanting to drive into Downtown and carpoolers who currently use the HOV lane. Lastly, the adoption of this system requires a change in consumer behavior. It is difficult to overcome consumer inertia to shift people to public transit use. The social pros and cons are summarized in Figure 6.3.

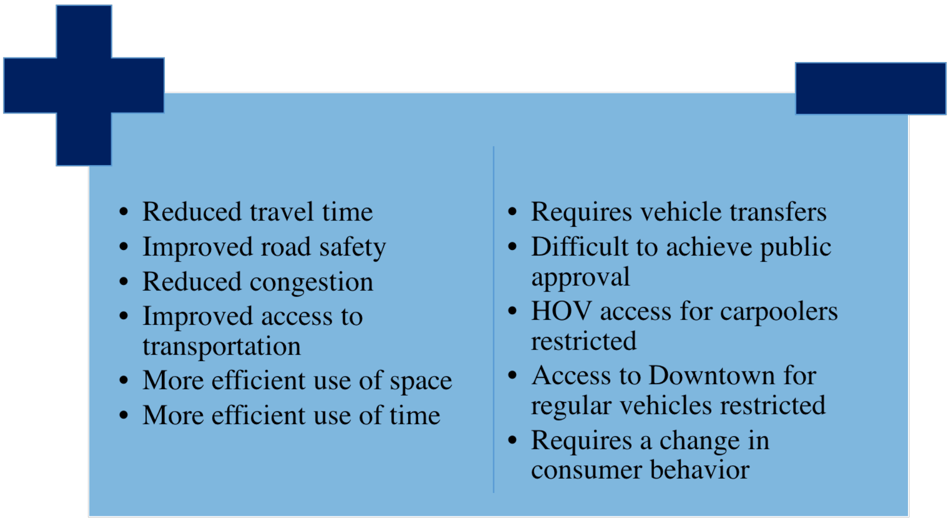

Fig. 6.3 Social Pros and Cons

6.2.2 Environmental

A new system should reduce transport-related emissions by replacing private vehicle use with public transit use. The emissions per passenger kilometer for the different components of the journey are shown in Figure 6.4. The first mile is excluded because it is assumed that commuters would drive to the P&R lots so the emissions would be the same across all three options.

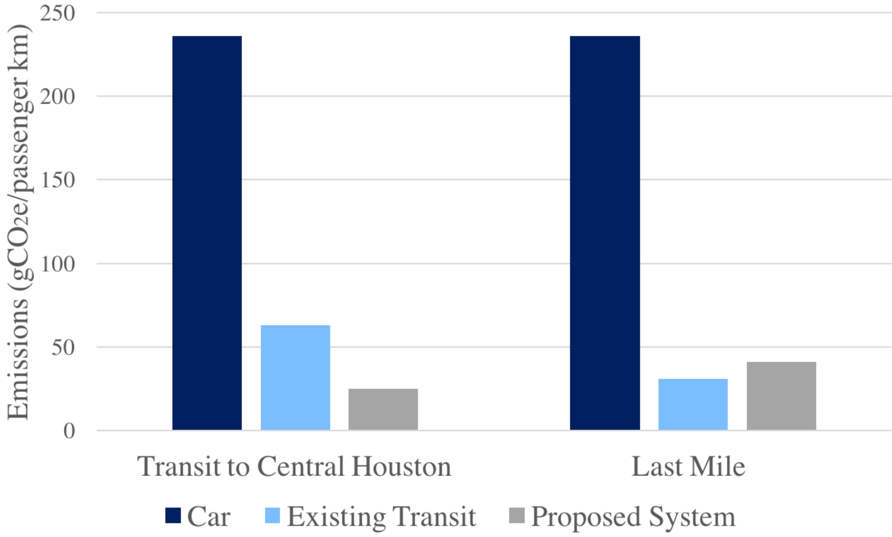

Fig. 6.4 Emissions Comparison per Journey Component by Mode

The total emissions over the integrated system for a journey from a suburban P&R to the final workplace in Downtown for the different modes of transport are illustrated in Figure 6.5.

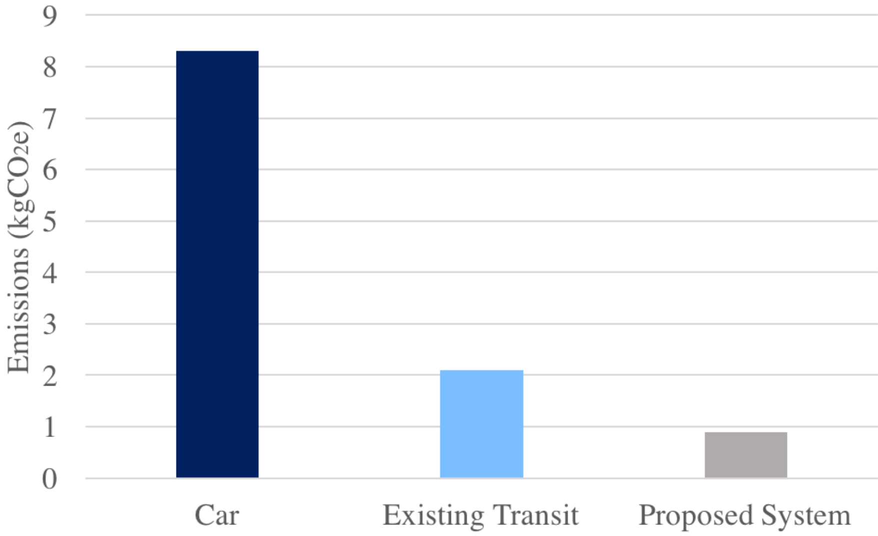

Fig. 6.5 Total Journey Emissions Comparison by Mode

If 28% of Houston's commuters switch from using cars to the autonomous system, this would save 406,000 tonnes of CO_2e each year. This is equivalent to a 2.5% reduction in Houston transport emissions [13].

This dissertation suggests that the autonomous system would reduce overall emissions while improving Houstonians' mobility. A good public transit system has the potential to shift commuters from personal vehicles to a public transit system, decrease the need for car ownership, and increase ride sharing. The positive effects benefit all Houstonians, not just those who choose to participate in the autonomous transit solution.

One drawbacks of this system is that, if commuters adopt the system only for the last mile element, emissions would increase compared to existing transit options. Moreover, the system could induce demand, increasing overall mobility and thus emissions. For example, the AV system downtown would allow employees to more easily travel for lunch, so more employees would travel by vehicle to go to lunch each day. The environmental pros and cons of the autonomous system are summarized in Figure 6.6,

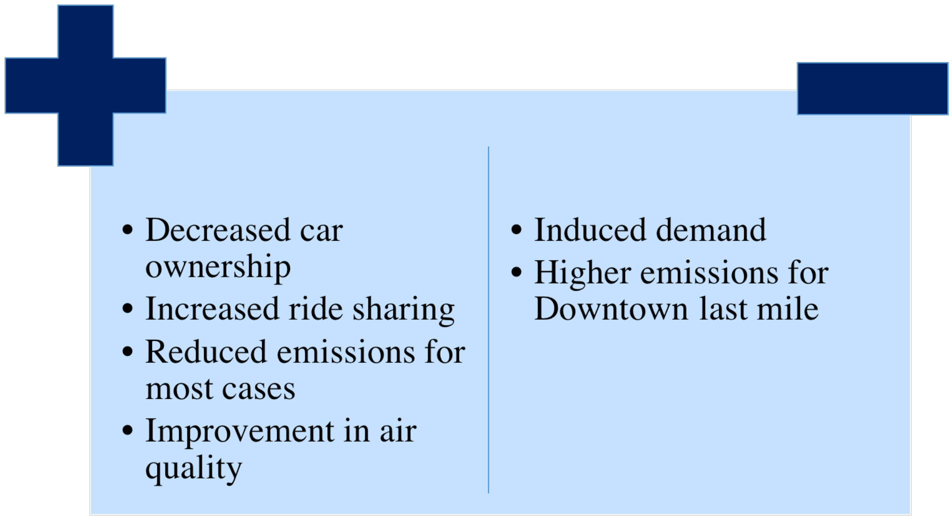

Fig. 6.6 Environmental Pros and Cons

6.2.3 Financial

This work suggests that an autonomous transit solution could be financially viable for Houston from both a consumer's and system operator's point of view.

Costs for the Commuter

From a consumer's point of view, the system could be priced at current public transit prices and still be profitable for the system operator. This way, AVs could provide a cheap transit option for Houstonians.

The cost comparison of driving, using existing transit, and using the autonomous system are displayed in Figure 6.7. These costs exclude the cost of the first mile because driving from one's home to the closest P&R would be the same across all three systems.

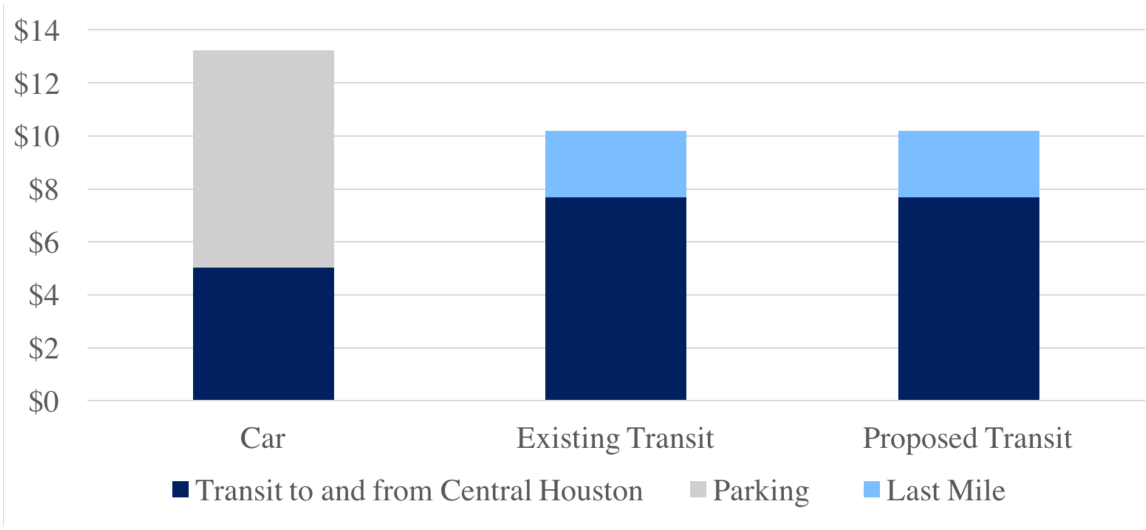

Fig. 6.7 Daily Cost Breakdown by Journey Component and Comparison by Mode

Replacing driving with the autonomous system would save a commuter $8 a day or $2,000 a year. The costs of driving previously calculated excluded the costs of owning and maintaining a vehicle. If those costs are included, driving costs 68¢ per mile or $36 per day [19]. If the integrated public transit system could encourage people to forfeit personal vehicle ownership, they could save $31 per day or $7,700 per year.

Costs for the City of Houston

The autonomous system with transit options in the Medical Center, Downtown, and from the suburbs to central Houston would cost a total of $1.4 billion (25% of Houston's 2019 budget) or $141 million each year for 10 years [122]. The cost breakdown is shown in Figure 6.8, where the MicroMetro system amounts to 75% of the costs.

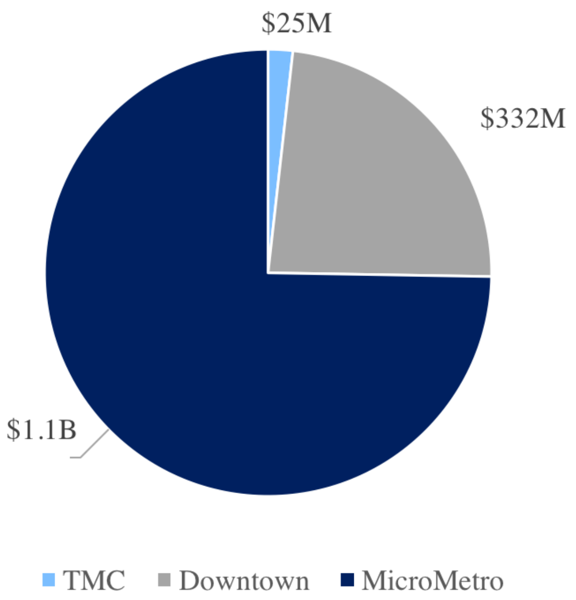

Fig. 6.8 Integrated Autonomous System Cost Breakdown

Financial Viability

From a system operator's point of view, the autonomous system is potentially self-financing via farebox revenues with sufficient profits to repay the cost of vehicles and infrastructure over a 10-year loan period. The final ridership levels or fare prices must surpass a certain threshold for the system to be profitable. The thresholds are summarized in Table 6.1.

Table 6.1 Autonomous System Ridership and Fare Threshold for Profitability

System	Ridership Threshold	Fare Threshold
Texas Medical Center	35%	$0.87
Downtown	22%	$0.69
MicroMetro	14%	$2.13

Using the assumptions outlined in previous chapters, the initial capital outlay, payback period, cumulative profits, and ROCE at the end of the 10 years are presented in Table 6.2.

Table 6.2 Autonomous System Initial Capital Outlay, Payback Period, Cumulative Profits After 10 Years, and ROCE After 10 Years

System	Initial Capital Outlay	Payback Period	Cumulative Profits	ROCE
Texas Medical Center	$8M	57 months	$11M	16%
Downtown	$68M	29 months	$275M	43%
MicroMetro	$675M	62 months	$836M	14%

Despite the cheap fare prices and potential for profitability, there are some financial drawbacks. For one, the system requires high upfront capital investment, which is risky before knowing if there will be consumer uptake. Secondly, high levels of ridership (higher than current levels of public transit use) are needed to ensure profitability. This means that the system must be good enough to turn new riders away from their cars. Otherwise, the system would not generate enough profits to payback the loans and would rely on alternative financial solutions. The financial pros and cons are summarized in Figure 6.9.

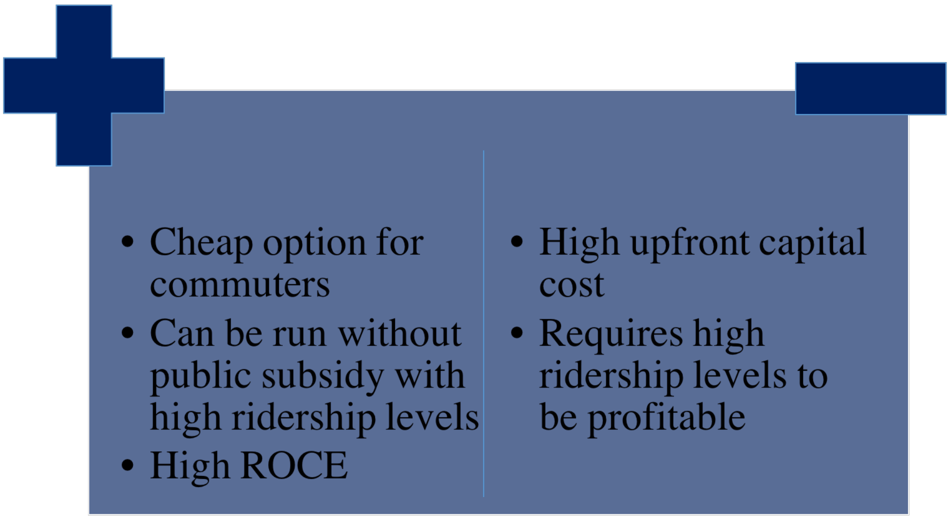

Fig. 6.9 Financial Pros and Cons

Financing Solution

If the systems failed to surpass the thresholds, pubic subsidies or other financing solutions would be necessary. Currently, 1% of Houston's 8.25% sales tax goes to METRO [25]. In 2018, METRO received $910 million in revenue just from the sales tax, which could be used to pay for the autonomous system [123]. In addition, METRO has already secured $3.5 to $4 billion from federal sources for the MetroNext plan, which could be diverted to pay for the autonomous system [25].

Comparison to MetroNext Plan

As previously discussed, Houston METRO has released a public transit plan for Houston. The costs and expected ridership of METRO's plan are detailed in Figure 6.10. The MetroNext plan and autonomous system comparison are shown in Table 6.3.

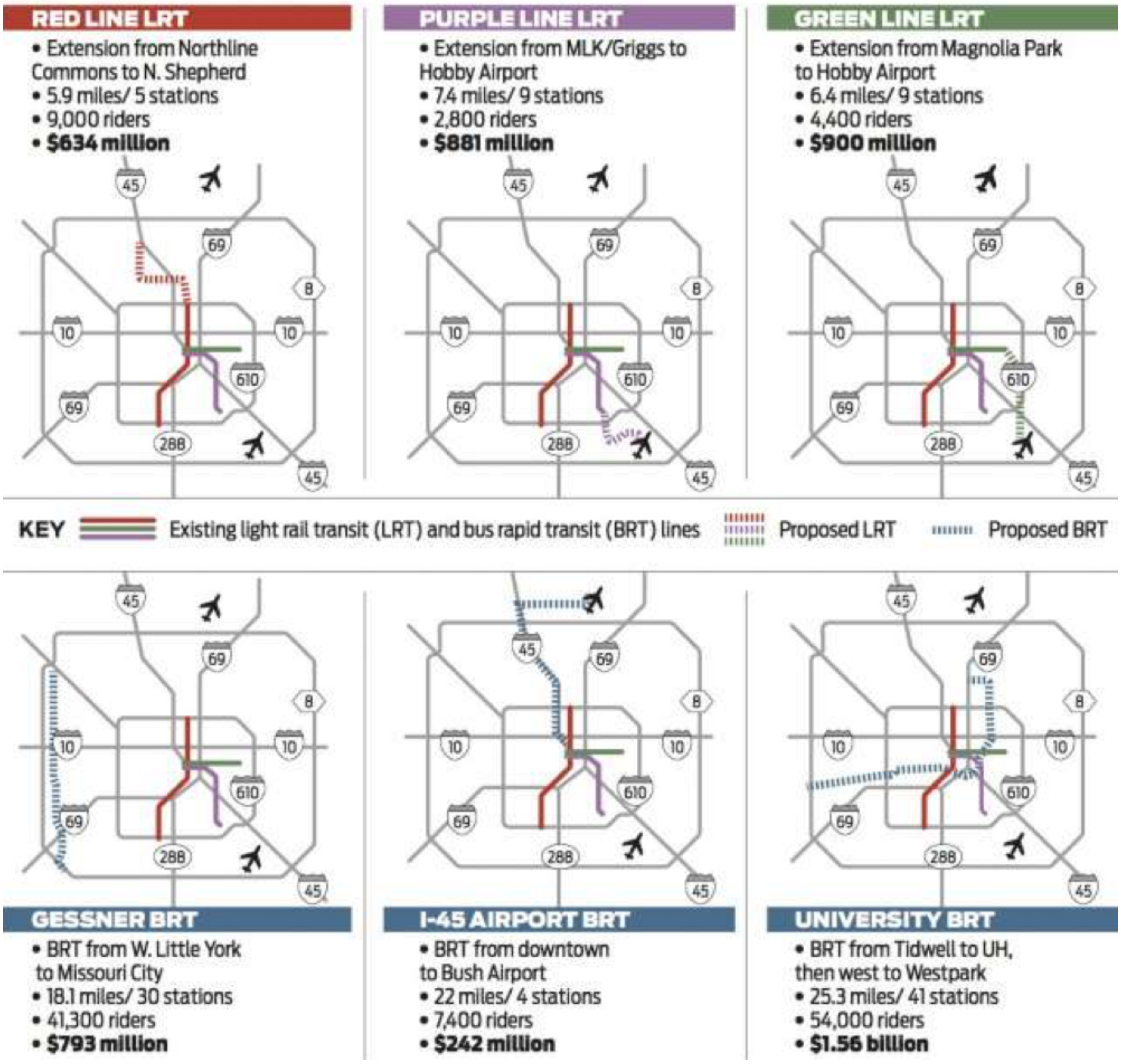

Fig. 6.10 METRONext Cost Components [25]

Table 6.3 MetroNext and Autonomous System Economics Comparison [25]

	MetroNext	Autonomous System
Total Cost	$7.5B	$1.4B
New Riders Captured	118,900	97,000
Cost per Rider Captured	$63,000	$14,000

The MetroNext plan captures more riders because it incorporates public transit systems in more geographical locations. Despite that, the autonomous system captures almost the same number of riders for a fraction of the cost.

The autonomous system has the capability of delivering upon METRO's goals set out in the MetroNext plan at a lower cost. MetroNext plans to make the HOV lanes bidirectional to accommodate reverse commuters [25]. The autonomous system would fulfill this aim. The planned HOV expansion of 110 miles of two-way HOV lanes and 8 new P&R stations is expected to cost $1.37 billion, 37% more than the MicroMetro system would cost [25].

The plan proposes high spending on transit systems that have proven unfit for Houston's needs. Critics of the plan decry the proposed spending on light rail [92] [25]. 1/3 of the costs ($2.5 billion) of the MetroNext plan go to expanding light rail while capturing relatively few riders [25]. Light rail must transport 5,000-10,000 people per hour for its high costs to be justified [104]. The three planned light rail expansions expect to capture 9,000, 2,800, and 4,400 new riders each day and therefore do not have a high enough demand to justify the price [25]. This expansion in light rail was proposed even though two of the three light rail lines operating in Houston have not reached their ridership goals [25]. In addition, light rail expansions in the similar cities of Los Angeles and Dallas have been followed by decreases in overall light rail ridership [105]. AVs should be explored as an alternative light rail.

This work has suggested that an autonomous system has the potential to reduce overall journey times, decrease transport emissions, be affordable for consumers, and be self-financing for a system operator. Hopefully this work can convince Houston transport leaders, including METRO, to consider autonomous vehicles when planning for the future of mass transit in Houston.

Chapter 7

Conclusion

This dissertation has explored the use of autonomous vehicles in Houston by applying AV systems to various geographical areas representing different segments of a commute. AVs as a possible solution to Houston's public transit issues were evaluated on a social, environmental, and financial basis. This work suggests that autonomous transport systems have great potential in Houston.

The method used to estimate the system requirements could be further improved upon by accounting for predicted population growth to improve demand estimates, by using more sophisticated models to determine journey time, by more thoroughly addressing infrastructure needs, by working with companies to better define the vehicle fleet with existing technologies, by including discounting and depreciation when estimating the economics, and by predicting Houston's future electricity breakdown when calculating emissions.

Despite these analytical shortcomings, the analysis still provided reasonable estimates for the main outputs: journey time, costs, and emissions. These outputs suggest that an autonomous system could potentially provide social benefits through reduced journey times, environmental benefits through reduced overall emissions (despite the increase in last-mile emissions for the Downtown portion), fare prices consistent with those of existing public transit, and profitability for the system operator via farebox revenues (provided the system surpasses ridership thresholds). Overall, an autonomous system seems to be a promising solution to Houston's public transit needs and should be considered when making plans for Houston's transit future.

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Appendix A

Last Mile:Texas Medical Center

A.1 Performance and Service Level Targets

A.1.1 Journey Time

Table A.1 Red Route Round Trip Journey Time

Stop	Travel Time at Vehicle Speed		
	10 mph	20 mph	30 mph
1	16 mins	5 mins	4 mins
2	2 mins	1 min	1 min
3	4 mins	2 mins	2 mins
4	4 mins	2 mins	2 mins
5	3 mins	1 min	1 min
Return to Lot	13 mins	5 mins	4 mins
Total	42 mins	16 mins	14 mins

Table A.2 White Route Round Trip Journey Time

Stop	Travel Time at Vehicle Speed		
	10 mph	20 mph	30 mph
1	6 mins	2 mins	2 mins
2	4 mins	2 mins	2 mins
3	3 mins	1 min	1 min
4	3 mins	1 min	1 min
5	2 mins	1 min	1 min
6	2 mins	1 min	1 min
Return to Lot	13 mins	5 mins	4 mins
Total	33 mins	13 mins	12 mins

Table A.3 Blue Route Round Trip Journey Time

Stop	Travel Time at Vehicle Speed		
	10 mph	20 mph	30 mph
1	8 mins	4 mins	3 mins
2	2 mins	1 min	1 min
3	3 mins	1 min	1 min
4	4 mins	2 mins	2 mins
5	3 mins	1 min	1 min
6	8 mins	3 mins	2 mins
7	2 mins	1 min	1 min
Return to Lot	8 mins	7 mins	7 mins
Total	38 mins	20 mins	18 mins

Table A.4 Red, White, and Blue Route Round Trip Journey Time

Route	Round Trip Journey Time		
	10 mph	20 mph	30 mph
Red	41 mins	16 mins	13 mins
White	32 mins	13 mins	11 mins
Blue	36 mins	21 mins	17 mins

A.1.2 Frequency

Table A.5 Comparison of Design Hour Frequency by Mode

	Pod (mins)	Shuttle (mins)	Light Rail (mins)
Red	.5	5-6	6
White	.7	5-10	10
Blue	3.8	10	6

Table A.6 Single Trip Journey Time Comparison of Different Transport Modes [60] [63] [59]

Mode	Route			
	Journey Element	Red	White	Blue
Pod	Walk to Pick-up	2 mins	3 mins	3 mins
	Wait	.5 mins	.7 mins	3.8 mins
	Vehicle Ride	9 mins	7 mins	11 mins
	Walk to Destination	2 mins	2 mins	2 mins
	Total	13.5 mins	12.7 mins	19.8 mins
Shuttle	Walk to Pick-up	2 mins	3 mins	3 mins
	Wait	5.5 mins	7.5 mins	10 mins
	Vehicle Ride	13 mins	8 mins	9 mins
	Walk to Destination	2 mins	2 mins	2 mins
	Total	22.5 mins	20.5 mins	24 mins
Light Rail	Walk to Pick-up	4 mins	4 mins	4 mins
	Wait	6 mins	6 mins	6 mins
	Vehicle Ride	8 mins	8 mins	8 mins
	Walk to Destination	9 mins	9 mins	9 mins
	Total	27 mins	27 mins	27 mins

A.2 Economics

A.2.1 Sensitivity Analysis

Cost of Vehicle

Table A.7 Low, Medium, and High Vehicle Costs with Varying Vehicle Price

Vehicle Price	$50,000	$100,000	$200,00
Annual Cost of Vehicles	$443,453	$886,906	$1,773,812

Interest Rate

Table A.8 Low, Medium, and High Vehicle Costs with Varying Interest Rates

Interest Rate	4%	6%	8%
Annual Cost of Vehicles	$886,906	$972,544	$1,062,833
Annual Cost of Stations	$161,299	$163,645	$166,119

Cost of Fuel

Table A.9 Low, Medium, and High Fuel Consumption Costs with Varying Electricity Prices

Electricity Price	6.25 cents	7.44 cents	8.46 cents
Annual Cost of Electricity	$287,696	$342,473	$389,425

Staff

Table A.10 Low, Medium, and High Staff Costs with Varying Overseer:Pod Ratio

Overseer:Pod Ratio	1:50	1:20	1:5
Annual Cost of Staff	$485,588	$689,988	$1,125,057

A.2.2 Economics Comparison

Shuttle Economics

Table B.9.

Table A.11 Annual Cost Comparison of Autonomous Pod System and Current Shuttle System

Cost Description	Pods	Shuttles
Vehicles	$886,906	$157,942
Stations	$161,299	$0
Fuel	$379,298	$45,265
Staff	$1,125,057	$1,226,750
Total Annual Costs	$2,372,992	$1,429,958
Cost Per Ride	$0.79	$1.04

A.2.3 Financial Viability

Table A.12 Annual Costs, Revenue, Profits, and Cumulative Profits Over 10 Year Period in Millions of Dollars

Year	Costs (millions)	Revenues (millions)	Profits (millions)	Cumulative Profits (millions)
1	$1.7	$1.9	$0.2	$0.2
2	$2.2	$3	$0.8	$1.0
3	$2.5	$3.7	$1.2	$2.2
4	$2.5	$3.7	$1.2	$3.4
5	$2.5	$3.7	$1.2	$4.6
6	$2.5	$3.7	$1.2	$5.8
7	$2.5	$3.7	$1.2	$7.0
8	$2.5	$3.7	$1.2	$8.2
9	$2.5	$3.7	$1.2	$9.4
10	$2.5	$3.7	$1.2	$10.6

A.3 Emissions

Table A.13 Peak and Average Emissions Comparison by Mode

	AV System	Bus System	Light Rail
Peak Emissions (g CO2eq/ passenger km)	18	21	31
Average Emissions (g CO2eq/ passenger km)	25	63	147

Appendix B

Downtown

B.1 Downtown Overview

Table B.1 Largest Downtown Houston Employers Ranked by Number of Employees [83]

Rank	Employer	Number of Employees
1	City of Houston	21,400
2	JP Morgan Chase	10,000
3	Chevron	8,000
4	Deloitte	2,500
5	Kinder Morgan	2,200
6	Houston Community College	2,200
7	CenterPoint Energy	1,800
8	Accenture	1,800
9	KBR	1,800
10	Ernst and Young	1,700
11	PricewaterhoustCoopers	1,700
12	University of Houston- Downtown	1,600
13	Enterprise Products Partners	1,489
14	KPMG	1,400
15	United Airlines	1,400
16	NRG Energy	1,400
17	St. Joseph Medical Center	1,300
18	Waste Management	1,300
19	LyondellBassell	1,000
20	TransCanada	975

B.2 Existing Transport Options

B.2.1 Bus

Table B.2 Downtown Bus Frequency [64]

Bus	Peak Frequency (mins)
6	30
11	30
32	30
44	20
51	15
52	15
54	10
82	6
85	10
102	30
108	60
137	12
160	15
161	15
162	15

B.3 Vehicle Fleet

B.3.1 Number of Vehicles

Congestion

Table B.3 Average Peak Frequency of 20-Passenger and 10-Passenger Shutles for Largest Employers

Employer	20-Passenger Shuttle Frequency	10-Passenger Shuttle Frequency
City of Houston	1 min	0.5 mins
JP Morgan Chase	2 mins	1 min
Chevron	3 mins	1 min
Deloitte	9 mins	4 mins
Kinder Morgan	10 mins	5 mins
Houston Community College	10 mins	5 mins
CenterPoint Energy	12 mins	6 mins
Accenture	12 mins	6 mins
KBR	13 mins	6 mins
Ernst and Young	13 mins	6 mins
PricewaterhoustCoopers	13 mins	7 mins
University of Houston- Downtown	14 mins	7 mins
Enterprise Products Partners	15 mins	7 mins
KPMG	16 mins	8 mins
United Airlines	16 mins	8 mins
NRG Energy	16 mins	8 mins
St. Joseph Medical Center	17 mins	8 mins
Waste Management	18 mins	9 mins
LyondellBassell	22 mins	11 mins
TransCanada	23 mins	11 mins

B.4 Economics

B.4.1 Sensitivity Analysis

Table B.4 Low, Medium, and High Vehicle Costs with Varying Vehicle Price

Vehicle Price	$30,000	$50,000	$70,000
Annual Cost of Vehicles	$8,095,278	$13,491,909	$18,888,672

Interest Rate

Table B.5 Low, Medium, and High Vehicle and Station Costs with Varying Interest Rates

Interest Rate	4%	6%	8%
Annual Cost of Vehicles	$8,095,278	$8,876,715	$9,700,795
Annual Cost of Stations	$121,494	$133,225	$145,593

Cost of Fuel

Table B.6 Low, Medium, and High Fuel Consumption Costs with Varying Electricity Prices

Electricity Price	6.25 cents	7.44 cents	8.46 cents
Annual Cost of Electricity	$898,978	$1,070,143	$1,216,856

Staff

Table B.7 Low, Medium, and High Staff Costs with Varying Overseer:Pod Ratio

Overseer:Pod Ratio	1:50	1:20	1:5
Annual Cost of Staff	$9,757,875	$12,405,241	$25,642,070

Lunchtime Use

Table B.8 Lunchtime Use Effect on Cost per Ride

	low	medium	high
% of Downtown Employees that use Pods for Lunch	56%	25%	6%
Cost Per Ride	$0.49	$0.63	$0.83

B.4.2 Economics Comparison

Table B.9 Cost Comparison by Mode [69]

	AV System	Bus System	Light Rail
Capital Costs	$8,216,772	$1,884,787	$3,558,423
Operating Costs	$26,847,800	$7,811,897	$19,201,758
Total Annual Costs	$35,064,572	$9,696,684	$22,760,181
Cost Per Ride	$0.67	$1.18	$3.45

B.4.3 Financial Viability

Table B.10 Annual Costs, Revenue, Profits, and Cumulative Profits Over 10 Year Period in Millions of Dollars

Year	Costs (millions)	Revenues (millions)	Profits (millions)	Cumulative Profits (millions)
1	$26	$44	$18	$18
2	$32	$56	$24	$42
3	$35	$64	$29	$71
4	$35	$64	$29	$100
5	$35	$64	$29	$129
6	$35	$64	$29	$158
7	$35	$64	$29	$187
8	$35	$64	$29	$216
9	$35	$64	$29	$245
10	$35	$64	$29	$274

B.5 Emissions

Table B.11 Emissions Comparison by Mode [80] [78] [79]

	AV System	Bus System	Light Rail
Emissions (gCO_2e/ passenger km)	41	21	31

B.5.1 Sensitivity Analysis

Table B.12 2-Seater Pod Emissions Sensitivity Analysis

Energy Requirement (kwh/km)	Emissions (gCO2/passenger km)
.18	43
.17	41
.13	31
.12	29
.09	21

Appendix C

Transit to Central Houston

C.1 Performance and Service Level Targets

C.1.1 Journey Time

Table C.1 MicroMetro and P&R Journey Times [59] [24]

P&R Station Names	Single Journey Time (mins)			
	P&R	60mph	85mph	99mph
Grand Parkway	50	29	20	17
Addicks	35	18	12	11
Kingsland	45	27	19	16
Spring	40	20	14	12
Kuykendahll	35	18	13	11
Townsend	35	20	14	12
Eastex	45	13	10	8
El Dorado	30	20	14	12
Fuqua	35	15	11	9
Monroe	30	10	7	6
West Bellfort	45	16	11	10
Westwood	30	14	10	9
Cypress	50	26	18	16
Northwest Station	40	22	15	13
West Little York	35	18	13	11
Weighted Average	42	21	15	13

C.1.2 Frequency

Table C.2 MicroMetro Ridership, Vehicle Departures Needed, and Frequency by Line

P&R Station Names	Ridership	Design Hour Departures	Frequency (mins)
Grand Parkway	3,800	64	1
Addicks	3,100	52	1
Kingsland	4,000	67	1
Spring	3,000	51	1
Kuykendahll	4,100	68	1
Townsend	3,600	60	1
Eastex	3,200	53	1
El Dorado	2,200	37	2
Fuqua	3,400	56	1
Monroe	1,900	31	2
West Bellfort	6,500	108	1
Westwood	1,300	22	3
Cypress	3,100	52	1
Northwest Station	3,000	49	1
West Little York	800	14	4

C.2 Economics

C.2.1 Sensitivity Analysis

Cost of Vehicle

Table C.3 Low, Medium, and High Vehicle Costs with Varying MicroMetro Price

Vehicle Price	$300,000	$600,000	$900,00
Annual Cost of Vehicles	$32,803,380	$65,606,760	$98,410,140

Interest Rate

Table C.4 Low, Medium, and High Vehicle Costs with Varying Interest Rates

Interest Rate	4%	6%	8%
Annual Cost of Vehicles	$65,606,760	$71,941,608	8,620,544
Annual Infrastructure Costs	6,374,901	$17,956,026	$19,623,033

Cost of Fuel

Table C.5 Low, Medium, and High Fuel Consumption Costs with Varying Electricity Prices

Electricity Price	6.25 cents	7.44 cents	8.46 cents
Annual Cost of Electricity	$13,210,404	$342,473	$15,021,508

Staff

Table C.6 Low, Medium, and High Staff Costs with Varying Overseer:Pod Ratio

Overseer:Pod Ratio	1:50	1:20	1:5
Annual Cost of Staff	$10,381,000	$5,017,000	$3,945,000

C.2.2 Financial Viability

Table C.7 Annual Costs, Revenue, Profits, and Cumulative Profits Over 10 Year Period in Millions of Dollars

Year	Costs (millions)	Revenues (millions)	Profits (millions)	Cumulative Profits (millions)
1	$94	$101	$7	$7
2	$101	$161	$60	$67
3	$106	$202	$96	$163
4	$106	$202	$96	$259
5	$106	$202	$96	$355
6	$106	$202	$96	$451
7	$106	$202	$96	$547
8	$106	$202	$96	$643
9	$106	$202	$96	$739
10	$106	$202	$96	$835

Appendix D

Sustainability Evaluation

D.1 Evaluation of Proposed System

D.1.1 Social

Table D.1 Single Trip Journey Time Breakdown and Comparison by Mode

	Car	Existing Transit	Proposed Transit
Drive to P&R or Highway	5 mins	5 mins	5 mins
Park and Walk to Bus	0 mins	2 mins	2 mins
Wait	0 mins	8 mins	1 mins
Transit to Central Houston	51 mins	42 mins	21 mins
Wait	0 mins	10 mins	1 mins
Ride to Work	6 mins	9 mins	6 mins
Park and Walk or Walk to Work	2 mins	2 mins	0 mins
Total	64 mins	78 mins	36 mins

D.1.2 Environmental

Table D.2 Round Trip Journey Emissions Breakdown and Comparison by Mode

	Car	Existing Transit	Proposed Transit
Transit to Central Houston (gCO_2e/passenger km)	236	63	25
Last Mile (gCO_2e/passenger km)	236	31	41
Total (kgCO_2e)	8	2	1

D.1.3 Financial

Table D.3 Round Trip Journey Cost Breakdown and Comparison by Mode

	Car	Existing Transit	Proposed Transit
Transit to Central Houston	\$2.51	\$3.84	\$2.01
Parking	\$8.20	\$0	\$0
Transit from P&R to Work	\$0	\$1.25	\$0.67
Transit from Work to P&R	\$0	\$1.25	\$0.67
Transit to Suburb	\$2.51	\$3.84	\$2.01
Total	\$13.22	\$10.18	\$6.66