High Capacity Transit for the Houston Region –

Creating a Multimodal System Approach for the 21st Century

An Opinion Paper by J. Sam Lott, TSU's Center for Transportation Training and Research, and Automated Mobility Services, LLC

March 25, 2019

Revision 1

Source: Houston-Galveston Area Council

The full Opinion Paper, the Executive Summary and the Appendices have been published as separate documents and each is available on request from H-GAC.

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Forward

This document has been prepared as an "opinion paper" which is intended to compliment and support H-GAC's Regional Transportation Plan and METRO's continuous planning for public transportation for the Houston Region. However, these opinions as presented herein are neither endorsed nor recommended by any specific entity, and in particular they are not endorsed or recommended by the H-GAC High Capacity Transit Task Force.

It should also be noted that information in this document is not necessarily referencing the very latest studies on any given topic. However, past reports which are referenced are documents I am familiar with, having led or participated in most of the studies that are identified. The points of emphasis herein are believed to not be contradictory to subsequent studies by others with respect to my broad concepts and ideas about high capacity transit for Houston.

I believe that a "crisis is coming" if we fail to comprehend the impacts of traffic congestion in the coming decades. This crisis can be managed if we do not neglect the opportunities to capture the moment when strategic decisions made now will allow us to progressively build the transit system Houston will need in the future.

J. Sam Lott, P.E. March 25, 2019
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Definition of Terms and Acronyms

Public Transit Technologies

HCT – High Capacity Transit, a dedicated transit system with a subregional or regional scale of service and the capacity to carry a large number of riders through a travel corridor

AV – Automated Vehicle – a connected and automated vehicle that is able to drive itself through automated controls along a roadway system without a human operator onboard; this technology is also being loosely called an “autonomous” vehicle.

AV Transit – an automated and connected vehicle that is carrying passengers within a defined operational domain and being operated under the auspices of a transit authority, a municipality, a regional/county government, or another quasi-governmental body such as a university or a management district.

AV Microtransit – a small automated transit vehicle with a capacity of 4 to 25 passengers, such as a minibus operated by a public agency or a contractor providing operations and maintenance of a vehicle fleet.

AV Bus – a large automated transit vehicle with a capacity of 40 to 60 passengers, operating in a manner similar to conventional transit services.

ATS – a fully automated transit system operating on a very high demand travel corridor and traveling along a protected, exclusive transitway using a vehicle technology that is considered a “fixed guideway” system comprising multi-vehicle consists physically coupled together.

Public Transit Operating Modes

AV BRT – a large AV bus operating on a high demand travel corridor with a fixed route and traveling within a dedicated/protected or semi-exclusive transitway to serve fixed station locations.

AV Circulator – an AV Microtransit minibus (or possibly an AV bus) operating within a Town Center, an Urban District or a Major Activity Center along a prescribed travel route which serves riders traveling between origin and destination stations generally within the defined center/district.

AV FM/LM – an AV Microtransit minibus (or possibly an AV bus) operating along travel routes that connect a HCT intermodal station with a nearby Town Center, Urban District or Major Activity Center.

ATN – an “automated transit network” service using AV Microtransit vehicles operated by a public agency and providing direct origin to destination service within a defined district or subregional area.

Private Fleet Operator Technologies and Modes

AV Taxi/Uber – an automated vehicle with an “automobile” classification that is being dispatched in a “ride hailing” mode such as Yellow Cab, Uber or Lyft; also referred to as “A-Taxi” within the AV industry.

TNC – a “transit network company” privately owned company providing automated vehicles with an “automobile” classification that is being dispatched in a scheduled service or “ride hailing” mode and which typically operates within a district or subregional area along the roadway network; this mode allows “shared ride” service within the defined area, such as Uber Pool or Lyft Line.

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1.0 Introduction – A Transportation Crisis is Coming

Houston will soon be the third largest metropolitan area in the United States, passing Chicago in the next few decades. With the prestige of this ranking comes the type of problems that the largest cities in the world must address, particularly in the provision of suitable transportation modes and travel options. And as a precursor to creating new transportation systems, the largest cities of the world must execute creative policy and planning with a long term view to stay ahead of the crushing burden of roadway congestion.

This paper was prepared during the period of time that the H-GAC High Capacity Transit Task Force has been assessing the potential ways in which high capacity transit systems and infrastructure could be incorporated into Houston's long range transportation plan. However, the paper presents only the author's opinions on what is the most sustainable approach that we can take to meet the challenges that are facing us as our region doubles in size between now and 2050. The concepts and opinions expressed herein do not represent the work of the Task Force or its recommendations.

The Impending Transportation Crisis – To state the problem in simple terms, the Houston-Galveston Region is facing massive roadway congestion on a scale that we have not experienced before. Our congestion problems will soon rival those of Los Angeles and New York, and we are falling behind even auto-centric Los Angeles in preparing for alternative travel modes to the automobile. To remain "sustainable" in our intra-regional travel mobility, multiple new options for travel modes must be created which are convenient and accessible for use when traveling within the region. We must begin to create an integrated multimodal transportation system built around a framework of High Capacity Transit (HCT) – a challenging endeavor that will take 30 years to implement.

The nature of our impending crisis is that the operating conditions on the region's roadway, freeway and tollway system will soon be at what traffic engineers classify as "level-of-service F" (LOS F). **Figure 1** shows the results of an operational analysis of roadway conditions for the year 2035 that was performed as part of the TxDOT high speed rail (HSR) ridership study in 2012. Although there have been new roadway projects defined and under construction since that study was performed with new travel demand forecasts now available from H-GAC as far out as 2045, the story that is told in the figure is representative of the improved roadway system now being planned or constructed, even with the benefits of advanced automobile technology allowing higher capacities for roadway lanes [1].

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[1] The study performed under the auspices of TxDOT applied a uniform average lane capacity of 2400 pcphpl (passenger cars per hour per lane), which is the highest recorded lane capacity with human drivers ever measured under optimal driving conditions. This lane capacity assumed high penetration of vehicles with automated driving systems, with some lanes performing at levels significantly higher than the average 2400 pcphpl applied throughout the freeway system when lanes with weaving movements and merge/diverge maneuvers are included in the average. In addition, the congestion queuing shown in **Figure** 1 assumed a density of vehicles occupying the lanes which was modeled with 25 foot vehicle spacing – a spacing level that would average a 10 foot space between each vehicle and the next vehicle in the congested flow queue at any congested flow speed.

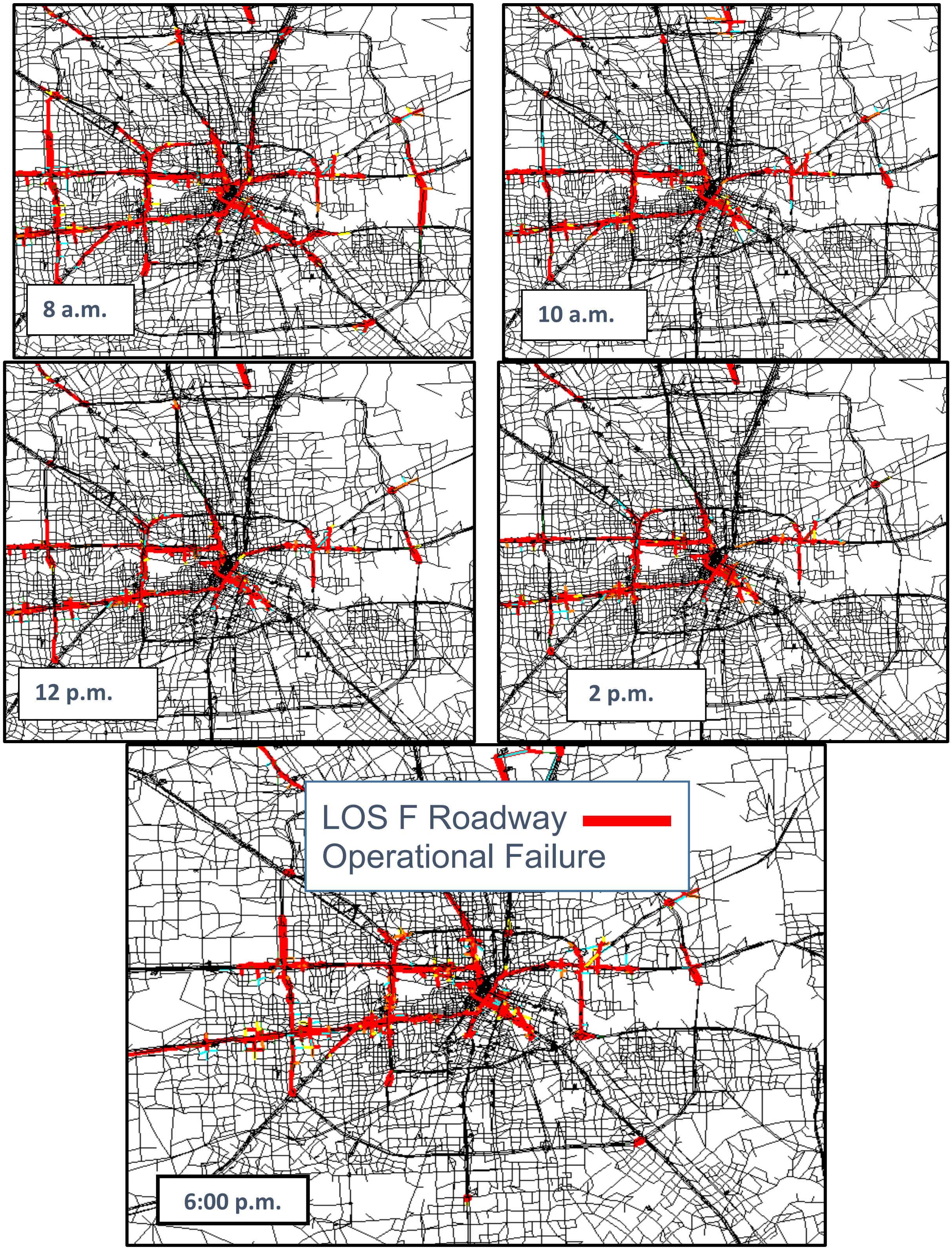

Figure 1 Forecast of Seriously Congested Operating Conditions by 2035 from 2012 TxDOT Study

The author believes that from 2035 and beyond, the operating conditions shown in **Figure 1** are still representative of how roadways will operate under the updated demand-to-capacity forecasts – even with the new roadway facilities and advanced automobile technology. And with regard to technology serving to increase lane throughput capacity, that consideration was actually applied in the 2012 study that produced the congestion forecasts shown in the Figure (see foot note 1.).

This situation of rapid growth is combined with our inability to build enough roadway capacity to absorb the increasing flood of new vehicles onto our roads, fueling a "transportation crisis" in which we have little time to plan, design and build new infrastructure in advance of the massive congestion. Drawing from the high capacity transit model that Los Angeles has been building for decades, the Houston Region must create a multimodal system that has a combination of commuter rail, regional metro rail, light rail transit (LRT), as well as advanced bus rapid transit (BRT) technologies, all operating within an integrated system.

The discussion that follows focuses on the opportunity of leveraging new technology to accelerate the availability of high capacity transit for day-to-day use within the Houston region. The application of new technology in transit service will be essential to help us mitigate the worsening roadway travel conditions, but it will not eliminate the roadway congestion that is driving our coming transportation crisis. Neither will new technology for automobiles eliminate the coming congestion.

In fact, the advent of automated technology for the automobile mode will actually have both positive and negative impacts. The reason for this assertion is that even with higher capacity on our existing roadways, there will also come an escalation in traffic activity when empty autonomous vehicles begin to move through the system.[2] The current development trajectory for automated vehicles adds new fleets of autonomous vehicles moving through the system and ballooning vehicle miles traveled (VMT).

The reality is that our whole forecast of future vehicle movements is missing vehicles that are not yet included in the traffic forecast studies such as the prior 2035 forecast shown in **Figure 1**. These "missing" vehicles are beginning to be recognized in the industry as important factors to include in future traffic forecasts, but there is not yet an established methodology for adding them into the travel demand modeling process[3].

Preparing for the "Storm" – The combination of growth that doubles the population of the region and the soon-to-be-experienced empty autonomous vehicle movements (i.e., vehicles operating without a human onboard) make absolutely certain that we will have massive congestion and progressively lower and lower operating speeds along our streets, highways and freeway/tollway system throughout the

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[2] The New Automobility: Lyft, Uber and the Future of American Cities, http://www.schallerconsult.com/rideservices/automobility.htm

[3] The momentum toward fully automated driving systems is shifting toward what is being termed as "fleet operations", with companies like Ford, GM, Uber, Lyft, Didi and Waymo preparing to launch large fleets of autonomous vehicles here in the United States. By its nature, the serving of "ride-hailing" passengers will inherently place many more empty-vehicle movements on the roads as vehicles are dead-headed back to the parts of the region where the demand for rides is the greatest. This type of vehicle movement is not currently represented in the regional travel demand models which generate vehicle-trips in association with person-trips. Furthermore, current studies in the industry are finding that there is not yet a suitable means to forecast these empty vehicle movements within conventional travel demand forecasting models.

region – even with the benefits of automation technology. This situation could be compared to a category 5 hurricane bearing down on the city, and there is nothing we can do to avert the storm. But what we can do is prepare to live in the midst of the storm.

The answer to our future mobility lies in the Houston region creating alternative ways to move around within the region that are separated from the main lanes of the arterial street, freeway and tollway system. This emphasis on high capacity transit involves creating an integrated, multimodal transportation system that provides access to and mobility within all employment and population centers throughout the region. Ultimately, there must be convenient means to reach all major destinations without the requirement of an automobile to make the trip.

Organization of This Document – Sections that follow first address the implications of deploying the emerging new automated vehicle technology in public transit services. Then the discussion turns to a look at the region's growth in terms of the transit ridership potential on the region's radial system of travel corridors connecting between urban districts, major activity centers and "town-living" centers. The challenge of moving large quantities of people between the suburban perimeters of the region where new population growth is exploding, and the urban core where the largest employment base will remain is then discussed. This requirement to transport huge quantities of people is addressed in a discussion of a conceptual optimum transit ridership forecast for 2045, which was prepared by H-GAC as a "Vision Plan" for High Capacity Transit large-scale deployment. This hypothetical forecast frames a discussion of the importance of high capacity transit combined with effective "first-mile/last-mile" transit.

The essential role that more conventional rail systems can play is discussed, specifically in the context of key corridors through which HCT configured as fixed guideway rail systems. It is this type of system that can provide suitable capacity to move large quantities of people, both during normal work days and during catastrophic conditions of severe weather events, evacuation crises, as well as other potential disruptions which could occur and hamper the new technology operations.

Working from the framework of information on what a multimodal HCT system will entail, a special case study is then addressed for the Westpark/Richmond Corridor, which is a new corridor needing high capacity transit and which already has an existing right-of-way that is under the control of public agencies. From this special case study and the other more general assessment of HCT that are given, a set of key conclusions concerning the need and urgency of creating an Integrated Regional Multimodal Systems is provided to complete the paper investigations.

Additional information is provided for reference in the appendices which cover the overall group of "service concepts" that have been envisioned through work of the HCT Task Force (**Appendix A**). As further information supporting the consideration of these service concepts, the additional appendices that draw from the author's experience address selected analytical studies of "automated transit networks" in which AV transit technology is deployed in smaller vehicles to provide access to a regional-scale high capacity transit system (**Appendix B**), examples of automated urban district circulation and FM/LM transit systems deployed on grade-separated transitways (**Appendix C**), theoretical concepts for the configuration of stations to serve the ultimate AV Transit system deployment (**Appendix D**), and concepts for consideration of ways to expand the capacity of the freight railroad network which would then allow for passenger rail service (**Appendix E**).

2.0 Transit Applications of the New Advanced Vehicle Technologies

The future holds great promise of providing a connected and integrated transit system in which different types of new transit technology are applied to enhance and improve accessibility to a large regional **High Capacity Transit (HCT)** system. The "conventional" transit technologies will certainly still include fixed guideway systems, but with increasing levels of automation. The "advanced" technologies will also include vehicles that today must be driven by humans, but in the future will be steered by artificial intelligence and automation controls which will be referred to in this paper as ***AV (automated vehicle) Transit***. In any applications of AV Transit technology, what will be different is that each single human – instead of driving one bus – will transition to a role actively engaged in managing the automated system. Each person within the operations staff will be able to manage a number of automated vehicles, allowing a shift towards operating many smaller vehicles.

Over the long term, public transit operations will trend toward providing a more customized service for each transit patron – more like automated taxis. Even "fixed route" bus operations will become increasingly "dynamic" as their route within the service corridor is adjusted in real-time to better suit the origin and destination trip patterns of the transit users. This is a trend that is already in operation throughout the world as transit agencies provide customized, demand-responsive service using smart phone app technology and dynamic bus routing/dispatching.

Under the AV Transit technology definition, a range of vehicle sizes – from 4 passenger "pods" to 60 passenger "buses"—will all be operating along a combination of city streets and arterials. But in locations where traffic congestion is a constant problem these advanced technology vehicles can be operated along dedicated transitways. These transitways may be grade-separated in areas where heavy traffic congestion clogs the city streets. This approach will be comparable to the new Post Oak/Uptown BRT line which will be on an exclusive aerial busway along several miles of the I-H610 West Loop, and then transition down to run along an at-grade transitway within the city street right-of-way when passing through the Uptown District.

For higher speed operations during the early years of deployment, the new ***AV Bus*** technologies will be operated along dedicated and protected transitways – such as what exists in the METRO owned and operated HOV lanes running along our major freeway corridors throughout the region.

<u>**New Types of Transit Service**</u> – One of the most important new types of services that AV Transit will foster is the provision of first-mile/last-mile (FM-LM) connections, by which smaller vehicles may be operated more cost effectively without an operator onboard every vehicle. As noted above, the same quantity of operations staff will be monitoring vehicle performance and operations across a larger fleet. These smaller and smarter vehicles will be able to offer not only fixed route connections between high demand trip generators, but also the AV Transit vehicles will offer a new type of service for which FTA has coined the term ***mobility-on-demand***. This concept provides customized route assignments and service patterns that adjust dynamically to fit changing demand patterns of the users throughout the day.

Figure 2 shows two examples of the earliest demonstrations of automated vehicle (AV) Transit technology which are currently operating at low speeds in pilot projects within pedestrian and urban street environments. The discussion that follows describes the early deployments of AV technology possible over the next few years, by which Houston will lead the industry in advanced technology applications.

Figure 3 illustrates an integrated multimodal transportation system with AV Transit services operating at the local town-center or urban district level to provide access to HCT subregional corridor and regional express transit services (such as AV Buses operating in HOV lanes). The key development that new advanced vehicle technology will bring is trip connectivity at both ends of the trip using the small automated vehicles in first-mile/last-mile service to circulate within the destination district or town center.

The discussion throughout this paper explores the tremendous benefit to transit users who are able to access high capacity transit using this small/smart vehicle AV Transit technology at one or at both ends of their trip.

The application of AV Transit technology to local district and town-center circulation, combined with first-mile/last-mile service will be generally referenced as ***AV Microtransit***[4], meaning public transit vehicles that are minibus size (e.g., 10-20 passenger vehicles) and even smaller. Ultimately, these AV Transit operations will apply full automation for both driverless operation and individual vehicle dispatching.

Table 1 shows the earliest timelines anticipated for AV Transit common use and application, as well as the early deployment prospects that were referenced in a recent TRB research project conducted by TSU's Center for Transportation Training and Research (CTTR)[5]. The table lists selected AV deployments that anticipated to be early deployment prospects in Houston. We can lead the industry as an early adopter of NHTSA/SAE Automation Level 4 technology applications allowing driverless vehicle operations.

Section 3 discusses further how all of the Service Concepts considered in this HCT study can be connected across the many town-centers, urban districts, major activity centers, and major travel corridors throughout the region. The author recommends that Houston quickly engage in an aggressive deployment of these advanced vehicle technologies.

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[4] The Wikipedia article on "Microtransit" represents the following explanation of this new terminology, which has been advanced primarily by "ride-share" proponents such as TNC or private transit services. In this paper, the term will be used as "AV Microtransit" to designate small, fully automated vehicles operating in public transit services.

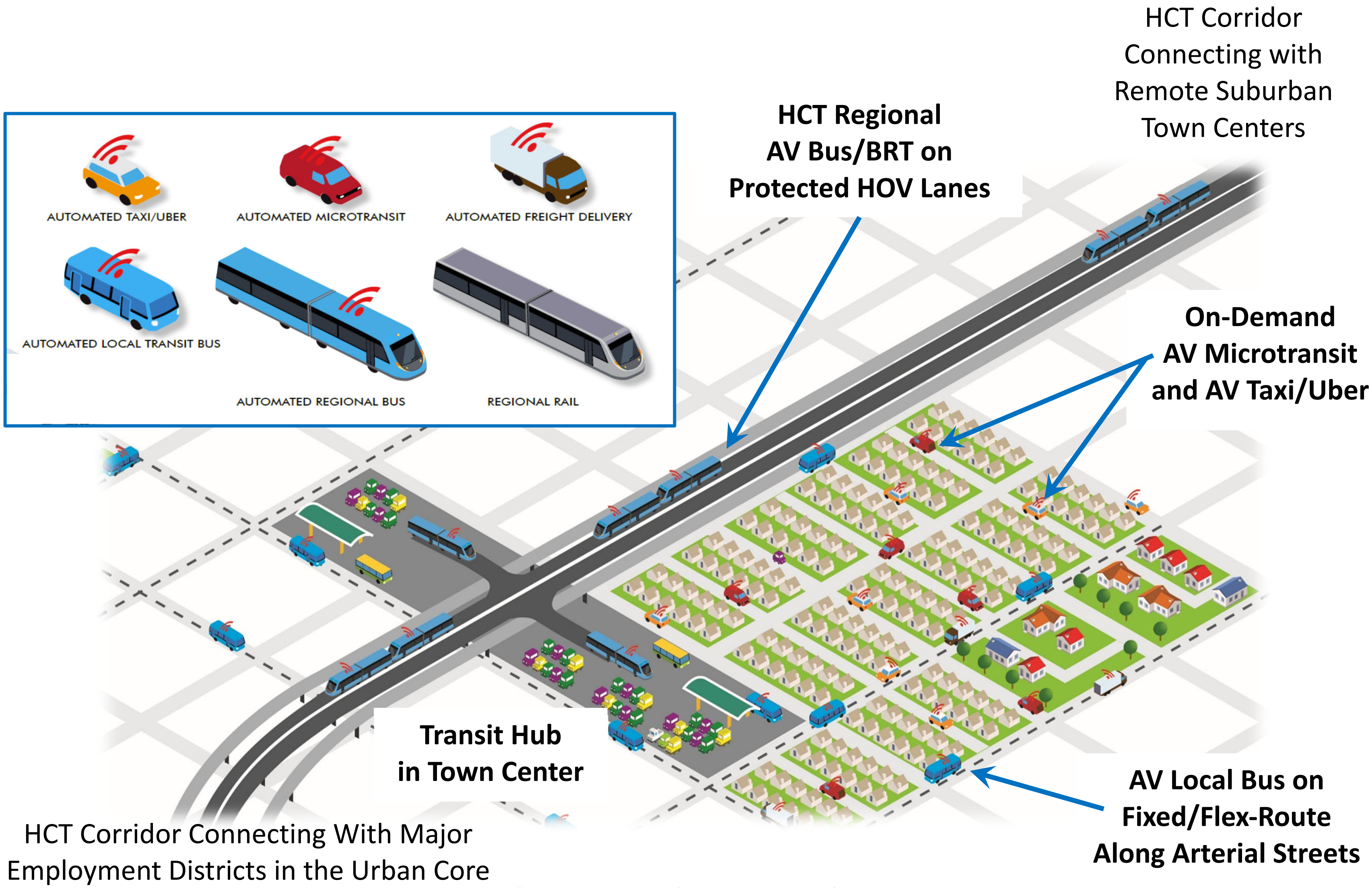
https://en.wikipedia.org/wiki/Microtransit

> "**Microtransit** is a form of Demand-responsive Transit. This technology enabled transit service offers flexible routing and/or flexible scheduling of minibus vehicles. Microtransit providers use instant exchange of information, enabling an extra real-time matching of demand (trip) and supply (driven vehicle) on top of an in-advance matching, which extends the accessibility of the transit service. Possible pick-up/drop-off stops are usually pre-defined to allow better routes' optimization. Conceptually, microtransit fits somewhere between private individual transportation (cars or taxicabs) and public mass transit (bus)."

[5] Functionality of Level 4 transit operations, AV technology readiness and the probable timeline for early deployment are discussed on pp. 18-22 in the research report titled "Impacts of Laws and Regulations on CV and AV Technology Introduction I Transit Operations"; ISBN 978-0-309-46687-5; TRB NCHRP Web-only Document 239, published 2017.

Navya Vehicle Operating in Las Vegas, NV – March 2018	EasyMile Vehicle Operating in Arlington, TX – March 2018

Figure 2 Examples of AV Medium Size Vehicle Technology Currently Operating in Demonstration Projects within the U.S.



Source: Houston-Galveston Area Council

Figure 3 AV Microtransit Circulation and FM/LM Systems Deployed In Town Centers and Major Activity Centers to Provide HCT Access Connections at Transit Hubs for Park & Ride Facilities

Table 1 Early AV Deployment Timeline for Houston Transit Applications

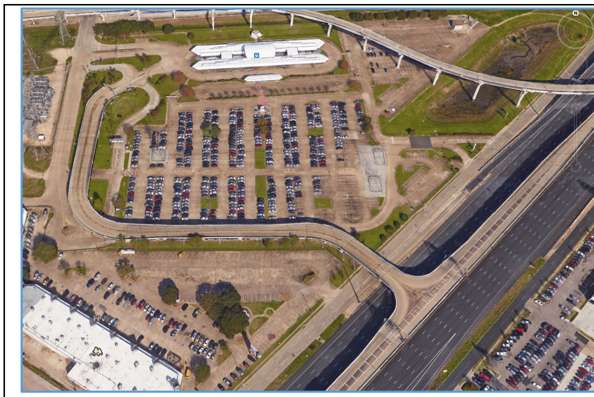
(Adapted version, based on table in source: NCHRP 20-102(02) Report – see footnote 5.)

Early Houston Services	Example Automated Machine Functions	Transit System Application	Potential Timeline for Early Houston-Deployment
Urban Center AV Circulator and First-Mile/Last-Mile Services	Automated driving, path determination and station berthing without a driver onboard at any time from origin to destination,	Automated Transit Route or Demand-Responsive Dispatch Operations; Empty Vehicle Repositioning/ Storage	Speeds Under 25mph - 2020-2025 Speeds Up to 40 mph – 2025-2030
HOV Lane and Transit Center High Capacity Transit System	Automated driving, path determination and station berthing without a driver onboard at any time from origin to destination,	Special Environment: Automated HOV with operator boarding at HOV Transit Center station stop	Speeds Up to 60 mph – 2025-2030
Dedicated BRT Lane System Operating in City Street Environment	Automated driving, path determination and station berthing without a driver onboard at any time from origin to destination,	Special Environment: Bus Rapid Transit in exclusive transitways with controlled at-grade crossings of city streets and pedestrianways	Speeds Under 25mph - 2020-2025 Speeds Up to 60 mph – 2025-2035

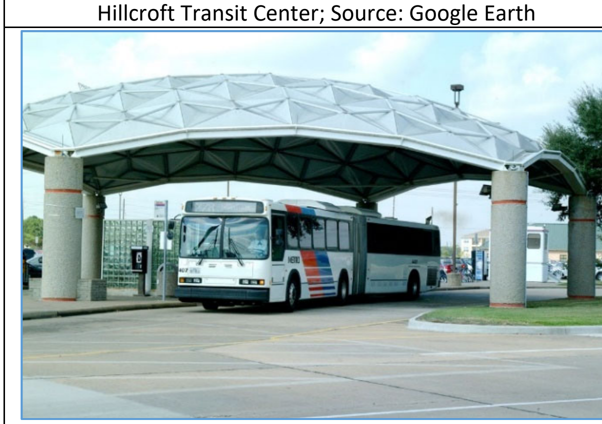
2.1 AV Bus Rapid Transit Lines

Houston has a transit asset that is unique among the major U.S. metropolitan regions. We have been investing in barrier protected high-occupancy vehicle (HOV) lanes for over 20 years, with about 100 miles of HOV lanes currently operating. Although some cities also have a few corridors with similar transitway configurations, the truly unique configuration features of the Houston METRO busway system are the elevated "direct connector" lanes passing above the freeway main lanes. These bridges connect HOV lanes in the center of the freeways with bus transit centers, as shown in **Figure 4**. The HOV connected transit centers and their associated park-and-ride lots are typically spaced along the corridor length about 5-10 miles apart.

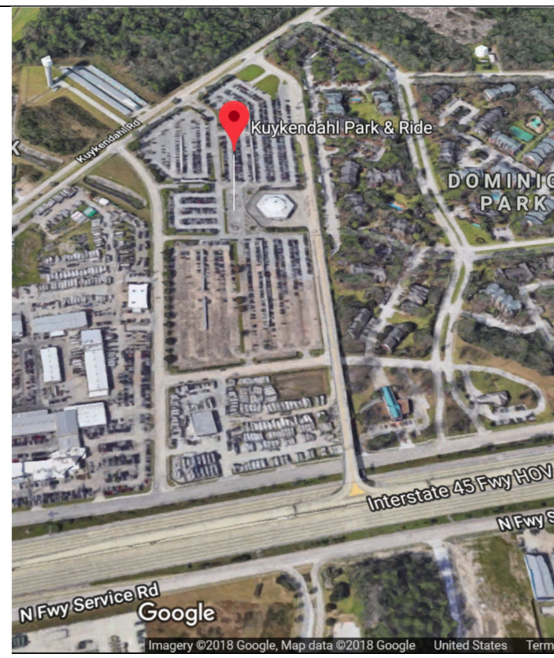
The configuration of operational routes and protected transitways is a form of Bus Rapid Transit, and it provides an excellent early deployment opportunity for AV Bus operations. In fact, AV Bus operations without a human operator (SAE Level 4 Automated Driving) will be possible in Houston's unique protected HOV lanes within the next five years.



Hillcroft Transit Center; Source: Google Earth



Source: Houston METRO



Metro Kuykendahl Park & Ride
Source: Google Maps

Figure 4 HOV Lane Direct Connector Lanes to Transit Center Bus Only Facilities

The TRB study for AV technology readiness (footnote 5 and **Table 1**) stated that protected operating environments such as HOV lanes will have early deployments of AV bus technology. This timeline can be accomplished in Houston at the earliest possible date using the Houston METRO HOV lane system.

We are uniquely positioned to see fully automated and self-driving buses operate between transit centers along the HOV lane system. Ultimately, this means that buses leaving the edge of the region will be able to operate unmanned all the way into the urban core, making stops at transit centers along the corridor and then returning to the HOV system without requiring an operator onboard.

AV Bus High Capacity HOV Lane System – With the dedication of the HOV system to automated buses will also come the capability to operate buses in platoons. Vehicle platooning technology has been tested in various forms for several decades, and as shown in **Figure 5** Houston METRO actually participated in proof-of-concept vehicle platooning tests more than 20 years ago on our system of HOV lanes[6]. Vehicle platooning involves automation controls which allow vehicles to "virtually couple" as they move through the HOV/BRT system like a train.

Figure 5 Houston METRO Buses in 1997 During Early Prototype Testing of Platooning Concepts

Bus platooning control technology took another step forward a few years later through R&D efforts of Toyota. **Figure 6** shows the platooning bus operations that occurred at the 2005 World Exposition in Aichi, Japan in which the automated buses carried about 2 million passengers over a period of 6 months.

From these early research and development efforts, the current R&D efforts in vehicle automation technology are again testing this operational feature with large truck platooning in particular being the most active research field at this time. In fact, Texas Transportation Institute is one of the leading entities performing research in truck platooning, with the current state of research summarized at the May 2018 3rd Annual TAMU Transportation Technology Conference[7].

Eventually, the capability of AV buses platooning through the HOV lane system will allow this key asset to be leveraged for an early Level 4 automation technology deployment in Houston. Through automation technology, the current HOV and "park and ride" bus operations will gradually increase its throughput capacity of passengers to a level needed for the ultimate high capacity transit system objectives. What is now mostly a commuter-based park and ride service could be transformed into a bi-directional BRT corridor service with direct connections to "off-line stations" in the form of transit centers along the freeway corridors where HOV lanes have been built.

[6] https://www.fhwa.dot.gov/publications/publicroads/97july/demo97.cfm
From this FHWA article on Automated Highway Systems that was published in 1997, an internal headline read: **Houston Metro Seeks to Lead the Way –** The Metropolitan Transit Authority of Harris County, Texas, (Houston Metro) is the only transit authority participating in Demo '97. Houston Metro is providing two New Flyer, 12.2-meter (40-foot) low-floor buses to participate in the demonstration runs. The buses will be outfitted at Carnegie-Mellon University with the hardware and software necessary to be full automated.

Houston Metro has identified automated highway technology as having potential for future application to the Houston HOV lane network as a cost-effective means of increasing vehicle throughput, and AHS will specifically be considered in Metro's long-range transportation plan. Houston Metro is seeking to be among the international leaders in the use of advanced technology to improve transportation.

[7] https://static.tti.tamu.edu/conferences/ttc17/presentations/session-a/lukuc.pdf

Source: Wikimedia, and: http://www.expo2005.or.jp/en/technology/imts.html)

Figure 6. Automated Buses Operated in Platoons at the 2005 Aichi World Expo

For this AV Bus system to reach the full capabilities and capacities that will be needed, we must be creating barrier protected, dual-lane HOV configurations which will allow continuous, bi-directional service all day long. **Figure 7** illustrates how this concept of automated bus technology operating in the HOV lane system will connect with AV Transit circulation systems operating within the local districts and town-centers along the corridor.

The prospect of Houston once again being a forerunner in advanced bus technology automation, as we were in 1997, is only possible if the system of continuous, barrier-protected HOV lanes is maintained within the existing freeways where currently built. We can be a leader in deploying Level 4 automation on a scale far larger than will be possible in other major cities of the world if we continue to develop this infrastructure.

Fortunately for those HOV lanes which METRO currently operates, in the future it will be possible to reconfigure the lanes which are now operating as high-occupancy/toll (HOT) lanes to a mode providing greater and greater availability for transit operations. As a strategic transit system planning exercise, the assessment of when those lanes operated by METRO should begin to be returned to dedicated HOV use is an important step for the near term. Use of the lanes where Level 4 bus operations occur should only be used by other vehicles which have are safety certified L-4 automated vehicles. The use of barrier protected HOV lanes as managed lanes open to any vehicles willing to pay the high tolls will need to be phased out as the deployment of automation technology becomes operational in Houston.

Most importantly, TxDOT's recent freeway reconstruction projects which have designs that reduce or eliminate the barrier protected HOV system from strategically important segments of our freeway network – particularly within the Urban Core – need to be evaluated further. If freeways are built without barrio protected HOV lanes, it will begin to cripple Houston's ability to build a suitable HCT system at the very time we should be enhancing and expanding these dedicated transit facilities. This design approach now becoming apparent needs to have immediate evaluation and assessment by our regional decision makers, since it could threaten the greatest benefits of an automated bus HCT system that efficiently connects with all other modes within the Urban Core.

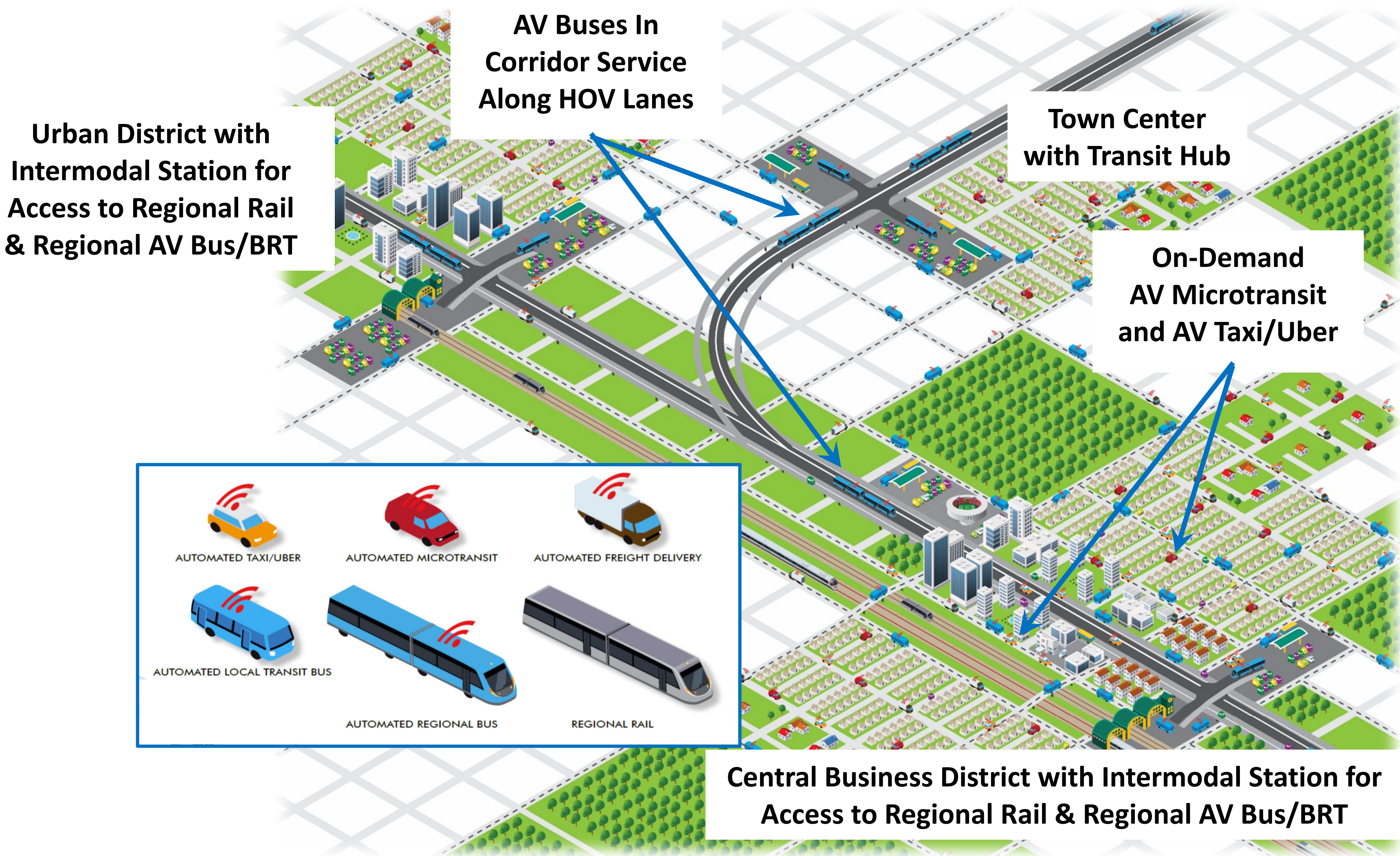


Figure 7 AV Buses in Subregional Corridor Service and Rail Systems in Regional Express Service are Connected at Major Intermodal Stations to Local AV Microtransit Systems Circulating Within the Urban Districts

Source: Houston-Galveston Area Council

2.2 AV Microtransit Circulation Systems and FM/LM Connectivity

Houston will soon become one of the early demonstration sites in the United States for a type of AV Microtransit technology which is being generically called in the industry an "AV Shuttle" application. Beginning in the Spring of 2019, a demonstration pilot project will begin passenger service under the auspices of Houston METRO, the City of Houston and TSU University. Known generally as the University District AV Transit Circulator System, the use of the vehicles will be under test and evaluation, initially operating as an on-campus circulator and in a second phase as a first-mile/last-mile connector between the TSU and U of H campuses to reach the METRO LRT system along Scott Street.

Phase 1 of the initial demonstration pilot will begin preparations for automated operations in late 2018, with the earliest phase of operations beginning about January of 2019. The subsequent Phase 2 of the early deployment project to reach the METRO LRT system is planned within a few years' time.

Figure 8 shows the ultimate application to the University District over the long term, with the early deployment occurring first along Tiger Walk on the TSU campus, and then extending to the edge of the U of H campus to reach the Purple Line LRT Station. Over the medium term, the AV line is planned to be extended to the Eastwood Transit Center, and then ultimately extensive service is envisioned to operate throughout the whole University District with a connection to Wheeler Intermodal Station on the Red Line.

Figure 2 (above) contains photos of several AV Microtransit technologies that have been operating in demonstration project within the United States over the past year. These photos show AV technology that represents the class of technology that will be operating on the TSU campus. The objective of this very early demonstration pilot is to develop an understating of operational and design requirements for not only the vehicles, but also the necessary stations, supporting communications systems, street/wayside infrastructure, as well as operations and maintenance facilities. The advancement of the early demonstration phase and the Phase 2 connection to METRO's LRT system will progress as soon as possible into an extension to reach Eastwood Transit Center, with an aerial photo showing its proximity to the north edge of the University of Houston campus in **Figure 9**.

In a future deployment phase the AV Transit Circulator System is envisioned to have operations that are of the type described "mobility-on-demand", with dispatching of individual vehicles occurring in response to ride requests made in real time. This concept is discussed in some detail in **Section 2.3** that follows.

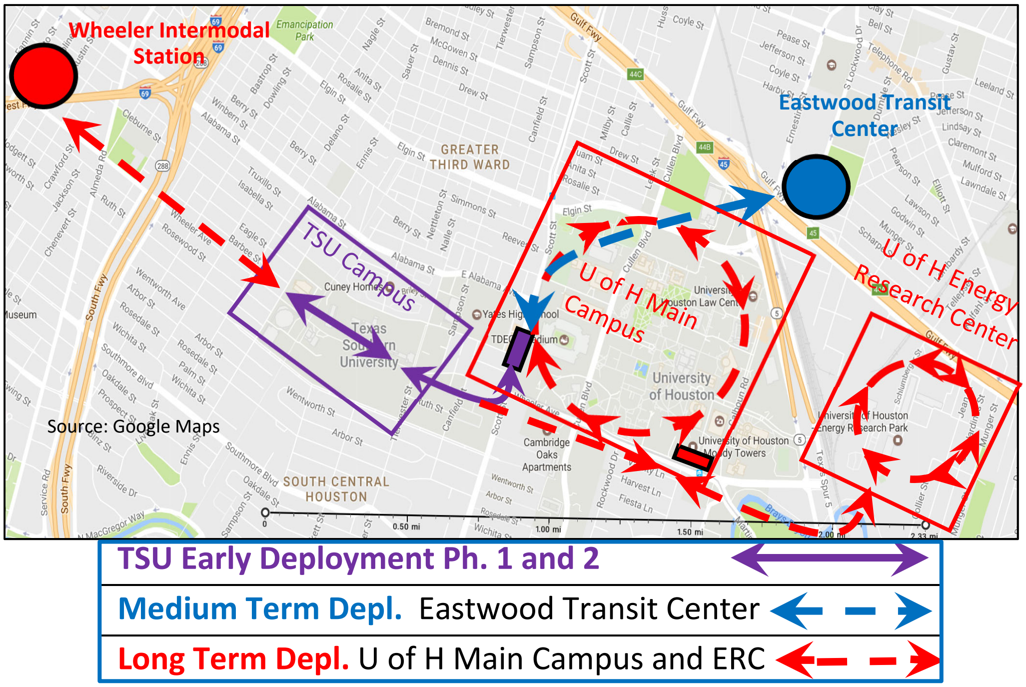


Figure 8 University District Phased Shuttle and Demand-Response AV Transport Service Long Term Implementation

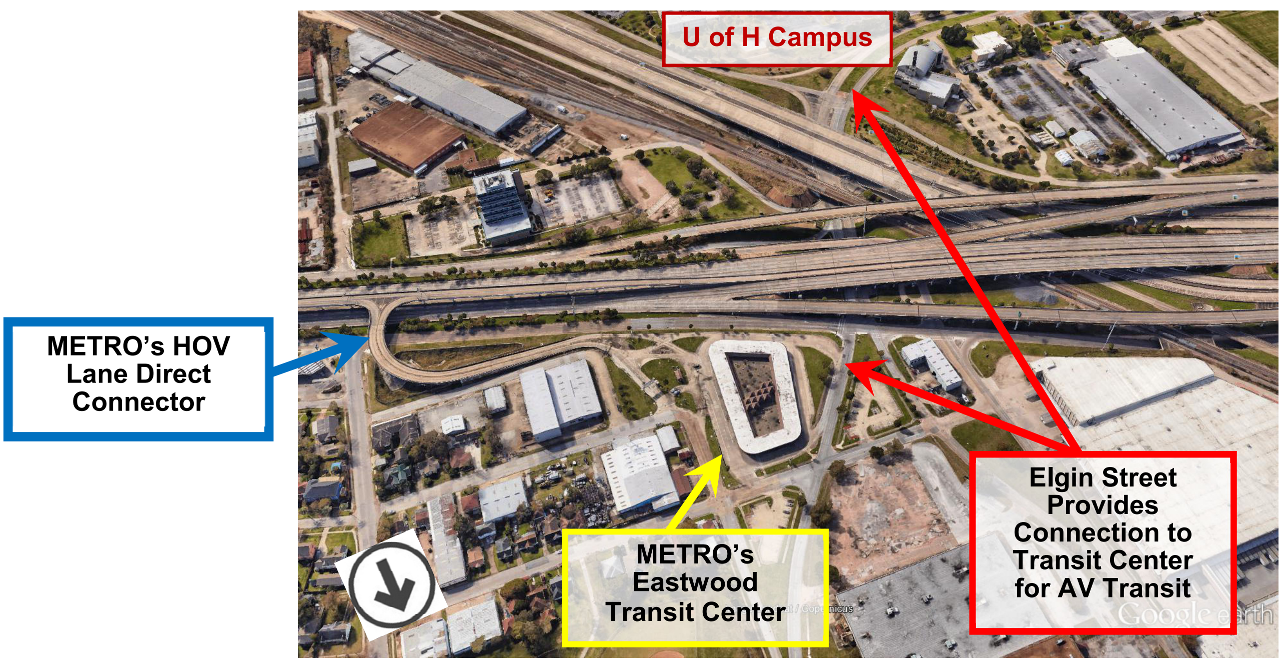


Figure 9 Eastwood Transit Center to be Service by the University District AV Circulator as a FM/LM Transit Connection Between the Campuses and the HCT Automated Buses Within the HOV System

Similar concepts of a district circulator system have been developed for the Texas Medical Center in past studies. Specifically, an automated transit circulator system operating on elevated guideways was studied. A highly conceptual illustration which describes the service is shown in **Figure 10**. This concept proposed over a decade ago envisioned the application of a form of automated guideway transit historically called an "automated people mover" system. This type of automated transit system has been operating in downtown Miami and downtown Jacksonville since the 1980s.

The emerging development of AV Transit technology by which the vehicle itself through an onboard control system not requiring "guideway" elements will allow the original TMC circulator concept to be provided by advanced technology AV Buses running on grade-separated transitways. When these higher capacity automated systems are combined with the new AV Microtransit technologies to provide first-mile/last-mile service along at-grade roadways, the concept illustration shown in **Figures 10 and 11** is similar to that shown above in **Figure 8** for the University District.

These two automated guideway transit technology examples shown in the photograph insets of **Figure 11** will in the future be replaced with AV Transit vehicles operating as a large AV Bus technology providing higher capacity circulation, combined with AV Microtransit vehicles operating at-grade in an automated transit network (ATN) service configuration. This figure illustrates the connectivity that will be possible at each end of a high capacity transit trip. ATN operating concepts where vehicles are dispatched in response to ride request "demand" calls (mobility-on-demand) are discussed in the following section.

Figure 12 shows the currently available range of vehicle sizes that are being offered by AV Microtransit technology developers. These sizes will be generally referred to in this paper as small (4 passenger), medium (10 passenger) and large (20 passenger) AV Microtransit vehicles – all of which will ultimately be capable of operating as an on-demand service in the ATN service mode. In practical applications, however, the small AV Microtransit vehicles are designed mostly for this type of transit network operations and the large AV Microtransit vehicles are designed primarily for fixed route service – but with real time, dynamic reconfiguration of route assignments for each bus as ridership demand patterns change.

Figure 13 shows a small AV Microtransit vehicle operating over a congested roadway on an aerial transitway. There are obvious benefits with transitway grade separation over the arterial street system in a dense urban district where traffic congestion is critically detrimental to transit operations.

This specific small vehicle technology application has been in service at London's Heathrow International Airport for 7 years, and the vehicle technology is a precursor of the new AV Microtransit technologies in that vehicles are not mechanically guided along the transitway. Rather, each vehicle is sensing its lateral and longitudinal location along its travel path and then steering itself from one station to the next.

The system installed at Heathrow Airport is also a small prototype of a technology designed to operate as an automated transit network (ATN) with passengers having a direct ride from their origin station to their destination station, and with the system providing a "personal" vehicle in response to a request of the user.

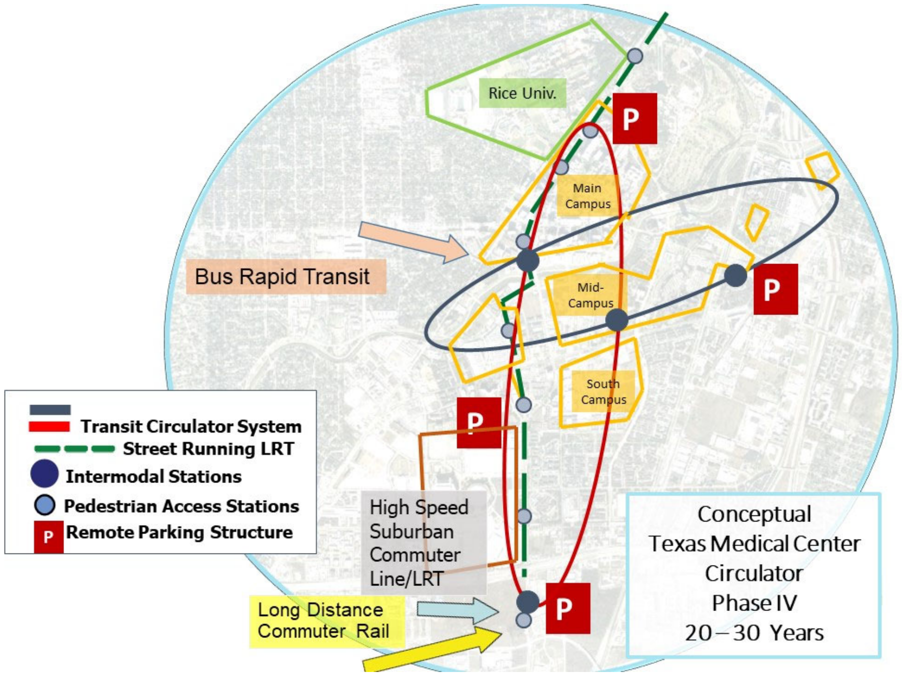


Figure 10 Conceptual Automated Transit Circulator System for Texas Medical Center

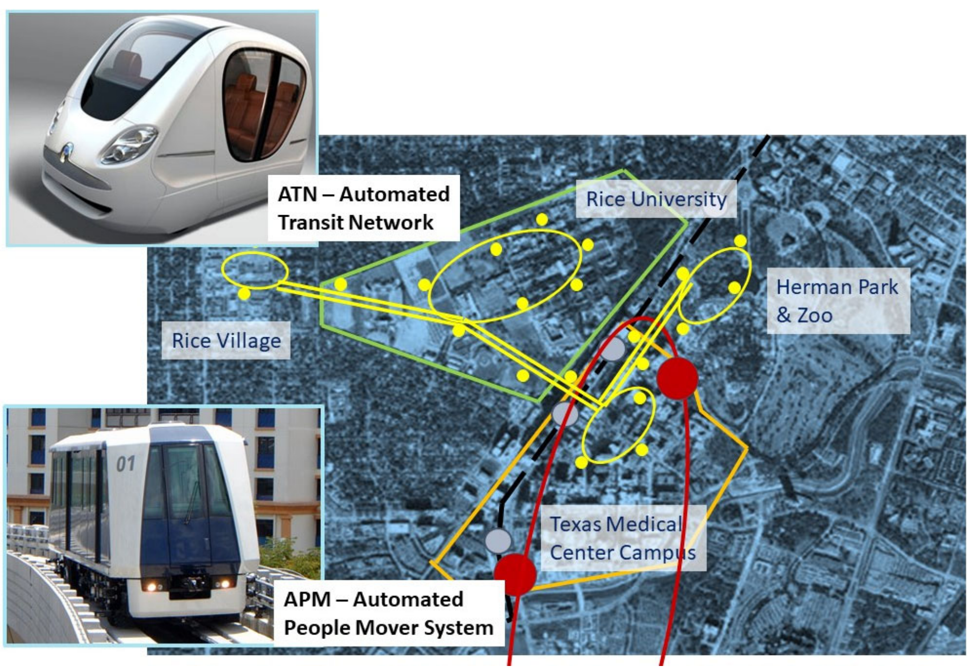


Figure 11 AV Microtransit Technology Operating as a FM/LM Connector – At-Grade Small Vehicle Local Area Circulator with Larger Vehicles Operating on Aerial Transitways Which Connect to HCT at Nearby Intermodal Stations

Source: Aurrigo, div. of RDM Group https://aurrigo.com/

Source: 2getthere www.2getthere.eu

Small 4 Passenger Microtransit Vehicles – Seated Passengers Only

Source: Navya https://navya.tech/en/

Source: Local Motors (Olli) https://localmotors.com/

Medium 10 Passenger Microtransit Vehicles – Seated and Standing Passengers

Source: 2getthere www.2getthere.eu

Source: 2getthere www.2getthere.eu

Large 20 Passenger Microtransit Vehicles – Seated and Standing Passengers

Figure 12 Examples of Three Basic Sizes of Vehicles Referred to as Microtransit Technologies and Applicable to Automated Transit Network Applications

Figure 13 Example of AV Transitway Passing Over Arterial Roadways with Heavy Traffic
Source: ULTra Global PRT

2.3   Flexibility of Operations

Advancements in AV technology are beginning to change our understanding of how transit services and fleet operations will occur 25 to 30 years from now. Although the transit industry is only at the very beginning of the changes that are coming, there is an understanding being gained of the new operating paradigm through initial demonstration pilots and through simulation-based analytical modeling studies.

New Transit Paradigm – Currently transit services are almost totally characterized by fixed route services with each vehicle operated by an on-board human driver according to a fixed schedule. Although fixed route services will continue to operate in the future, they will be gradually converted to operations applying AV Transit automation across the entire transit system. This transformation will allow fixed route service to also evolve in ways that can provide more frequent service with diversity of routes, thereby providing to each transit user a greater selection of possible destinations and more customized service for their specific travel path.

Ultimately automation will allow the role of operations employees to transition from the current requirement of one employee driving one large bus along a fixed route into a future role of one operations employee overseeing the operations of many smaller AV Microtransit automated vehicles. Based in local operations centers spread throughout the region, personnel will also be moving through the system to provide rapid response to customer needs, to address equipment performance issues, and to manage station operations when required. In essence the existing level of staffing should be able to provide much higher transit system capacity and much better service, resulting in increasing transit ridership without requiring a larger operations staff.

This new paradigm also means that AV transit technology will provide a capability to dynamically adjust operations to fit the changing demand patterns throughout the day. In recent years this new concept of transit services is being referred to as "mobility-on-demand"[8]. Most have identified this concept as representative of the services provided by Uber and Lyft, which are a relatively new type of "ride-hailing" service that is also now commonly being called a "transportation network company" (TNC).

In the field of automated guideway transit, this mode of operations has been called ***Automated Transit Network (ATN)*** service. For purposes of this Opinion Paper the term ATN will also be applied to AV Microtransit vehicles operating along at-grade roadways and on dedicated transitways when they are continuously dispatched in real-time by a supervisory system acting in response to specific transit user demand calls for service.

In ATN operations, the system's automated dispatching typically occurs in real-time, and provides the utility of a passenger boarding a vehicle at any station, designating their desired destination station and then having the vehicle take them directly to their destination with no stops (or minimal stops) along the way. This highly customized routing, to serve transit passengers with a very high level of convenience and rapid travel times, is the highest level of service that an ***AV Microtransit Circulator*** **and** ***First-Mile/Last-Mile (FM/LM)*** service can provide at each end of a transit user's high capacity transit trip.

When technology becomes capable of fully automating the dispatching of many smaller vehicles in response to patrons' demand-calls for service, the following service attributes will be realized:

- Transit Service will provide a more convenient and time-efficient trip for patrons, due to:
  - shorter waiting times when a trip is initiated, and
  - a more direct route between the origin and destination.
- Transit Operations will be more energy efficient and cost-effective overall, due to:
  - transit vehicles dispatching only when service is requested,
  - smaller vehicles being deployed with a higher average load factor throughout the day,
  - transit vehicles remaining dormant during periods of the day when demand drops – held in prepared storage/dwelling locations when not in service carrying passengers.

Other dynamic dispatching modes within the new operational paradigm will involve "flex-routes", or also called "hybrid routes"[9]. AV transit vehicles on a basic fixed route can be dynamically diverted off of the route to provide a more customized service to one or more passengers onboard, or for a transit user waiting for a pick-up.

[8] Mobility on Demand (MOD) is a component of Mobility as a Service (MaaS) – an important and still developing field of transportation planning and operations management. MaaS provides a seamless connection to an individual's mobility needs through information technology applications. For one specific trip it may be a "single-seat ride" solution, and for a second specific trip in may be a multimodal solution with multiple transfers between modes. MaaS can be described as a technology facilitated information source that brings all mobility services into the one information and trip planning block/hub, combined with a single means of trip reservations (if applicable) and payment. It allows end users to seamlessly build their mobility solution based on a given set of criteria which do not prioritize one type of mode over another. However, where the MaaS solution has been implemented, mass transit gains the most benefit of all the modes. *Source: Danny Silva, Houston METRO Service Planning Dept.*

[9] Samples of dynamic routing, with real-time dispatching of buses from fixed routes to deviate onto another route to pick up riders at stops from which there has been a demand/request, can be found operating today in Detroit, Los Angeles, and several European cities. Preliminary results show a reduction in passenger wait times and an increased efficiency in operational revenue hours. *Source: Danny Silva, Houston METRO Service Planning Dept.*

AV Microtransit Implications for HCT Ridership – In the discussion of high capacity transit service concepts that has occurred within the region over the past few years, the automation of large buses has been recognized as a technology application well suited for METRO's system of HOV Lanes and Transit Centers. However, the new types of AV Microtransit technology with smaller vehicles providing first-mile/last-mile services will be equally important as they make high capacity transit lines work much more effectively. This new level of convenience and utility will attract a greater percentage of travelers to use the public transit mode.

Because of the greater complexity of the operations for ATN type of service, the use of simulations has been used by the author in the past 15 years to study shared-ride services when the vehicles are operating with "on-demand" dispatching features. A variety of locations have been studied at which HCT rail systems located in proximity to urban districts or major activity centers, typically involving case studies of FM/LM connections using smaller automated transit vehicles. The results of these conceptual studies are addressed further in the next section, and a summary of the analyses performed is provided in **Appendix B**, titled "Automated Transit Network Technology Applications for First-Mile/Last-Mile Connections to High Capacity Transit."

2.4 Infrastructure and Facility Requirements

Transit operations have always utilized dedicated communications systems for bus and train operations, and this type of transit infrastructure is expected to continue in use. However, the communications systems connecting each vehicle with an operations center, as well as the communications infrastructure needed to communicate with passengers and ensure their safety at station stops served by AV buses and microtransit vehicles, will increase in complexity. The complexity of operations within intermodal facilities, and the configuration of the station "platforms" where passengers board and alight the transit vehicles must evolve along with the AV technology.

Data Communications Systems – With the advent of automation, the amount of data being transmitted to and from each vehicle as well as the increasing quantity of vehicles will require a more robust communications system. For example, the "station" stops at which passengers board and alight the transit vehicles will require additional systems for security and safety of passengers since a human operations employee may not be present at each station location. Means of voice communications as well as video monitoring will become standard infrastructure throughout the operating system, although vehicle-mounted cameras may provide sufficient monitoring for locations remote from conventional "station" locations.

In addition, the infrastructure located throughout the transit network will require additional equipment to connect the vehicle to the traffic signal control system – typically called "V2I" for vehicle-to-infrastructure communications. Other equipment infrastructure will also be required to assist the vehicle in its continuous determination of it's precisely location (called "localization"), especially when weather, buildings or overhanging structures shield it from the conventional satellite-based navigation systems.

There may also be a practical role for data carrier services which could be contracted to a private source as the new 5G communications infrastructure matures.

Facility Requirements – Operations personnel will gradually move from a presence on or near the vehicles to locations where operations centers have been established. From these facilities the "roving" operations staff will either be dispatched to assist passengers, recover a vehicle that may have performance issues or even failed in some manner, or even to take control of a vehicle remotely from the operations center to resolve an operational issue or to remove a failed vehicle from service.

Station facility footprints will become larger in some locations to accommodate multiple small vehicles stopping and dwelling at the same time, especially within transit hub locations located throughout a district or along transit corridors. These will evolve to resemble the METRO transit centers spaced along the HOV system, but designed to serve both large and small transit vehicles. The topic of station configuration is addressed further in **Section 3.3**.

Of particular interest to this paper are the implications of AV technology to features and configurations of intermodal facilities when HCT services of a subregional corridor service type as well as regional express service type all connect in one place with local transit services. At these intermodal facilities, the AV Microtransit services that provide FM/LM connections to the adjacent urban districts and major activity centers must also be accommodated, with all vehicle types of the various transit services efficiently accessing and egressing the intermodal facilities without delays imposed by traffic congestion.

Appendix B summarizes relevant studies of HCT intermodal stations that would be served by FM/LM AV Microtransit vehicles providing shared-ride mobility-on-demand. From these studies, the following surge flow conditions typify the type of demands that small microtransit vehicles operating in network configurations must serve.

Low Activity Level HCT Intermodal Station Benchmark

- Peak 5 Minute Flow-in (Brdg.+Altg.) = 60 pass.
    - Peak 5 Min. Equivalent Hourly Rate = 750 pph

Medium Activity Level HCT Intermodal Station Benchmark

- Peak 5 Minute Flow-in (Brdg.+Altg.) = 200 pass.
    - Peak 5 Min. Equivalent Hourly Rate = 2,500 pph

High Activity-Level HCT Intermodal Station Benchmark

- Peak 5 Minute Flow-in (Brdg.+Altg.) = 420 pass.
    - Peak 5 Min. Equivalent Hourly Rate = 5,000 pph

These levels of surge flow demands directly affect the minimum number of vehicle berths that must be provided for the FM/LM services in the HCT intermodal station facilities.

Barrier Protected HOV Lane System – But most important among all infrastructure and facility requirements is the continued expansion and improvements to our barrier-protected system of HOV Lanes. The existing system still has many critically important locations where the bus must pass out of the protected operating environment to enter the main lanes of the freeway.

These gaps need to be filled with suitably protected HOV lanes. Furthermore, existing single-sections currently operating as unidirectional reversible lanes need to be expanded to dual bidirectional lanes in order to allow continuous, all-day AV Bus service. In fact, the filling of the current gaps within the existing HOV lane system where the barrier protection is missing is important to address for the purpose of increasing safety today and providing higher travel priority to high-capacity transit vehicles along the freeway/tollway corridors.

3.0 Mobility Through an Integrated and Connected Multimodal Transit System

"Mobility" is difficult to quantify as a performance metric, but it is a useful concept when it is viewed as measuring transportation system accessibility and utility. In general, measurements of mobility that go beyond simple travel time can be understood as attributes of a modal option by which a person can easily travel during normal waking times of the day – both within the region overall and within the core of the city in particular. Some attributes of a transportation system that help define "mobility" are the user's convenience, comfort, safety and affordability of travel between their principle trip origin and principle destination. To accomplish "mobility" in the decades to come on a comparable level to what we enjoy with our private automobiles will require that a high capacity transit system be carefully designed at all levels across the multimodal spectrum.

Fundamental to achieving mobility is the fact that for the transportation system to be effective and useful to all Houstonians, it must also be accessible to everyone. Therefore, discussion below addresses how all the public transit modes can be interconnected to provide accessibility and mobility, with a particular focus on the center of the urban core where all of the modes come together in a concentration much denser that other parts of the region. This is not in any way indicating that multimodal transit systems with good connectivity are not also important at many other places in the region; however, this paper is written with a particular focus on the urban core. The center of the region is the most critically important and most complicated subregional area. Here, more than anywhere else, the time to plan, design, finance and build the necessary infrastructure will take a focused effort over the next 20 to 30 years. Extensions of the principles herein can also be applied to many other large and small urban districts, major activity centers and town centers around the region.

H-GAC has been investigating the "Service Concepts" that should be considered as part of our multimodal transportation system. These Service Concepts are summarized in the following list. It should be noted that all are defined as providing bi-directional transit services all day long – except for Regional Commuter/Express Service which operates during the morning and evening commute periods.

<u>HCT Service Concepts</u>

- Local
  - First-Mile/Last-Mile Service
  - District Circulator Service
  - Local Circulation and Connectivity
- Subregional
  - Subregional Corridor and Inter-Nodal Service
- Regional
  - Mega-Region Service
  - Regional Commuter/Express Service

These Service Concepts are discussed further in **Appendix A**. They are also addressed in **Section 4** below, which discusses the example of a particular high demand corridor and a selection of technology options for several Service Concept types are compared for application to that corridor.

Each of the Services Concepts have been studied for use using H-GAC's continuing analysis process of roadway traffic and transit ridership travel demand modeling. A possible scenario of these Regional and Subregional Service Concept deployments has been specifically defined for the each of the region's major travel corridors as part of H-GAC's transit ridership forecast for a conceptual high-transit deployment scenario. The set of Service Concepts listed above, with their characteristic frequency of service and travel times, have been included in this analysis process to quantify possible transit ridership demand. It is important to note that the assumptions of service frequency and available carrying capacity of the hypothetical transit system are very optimistic and "aggressive".

The demand patterns forecast through H-GAC's recent 2045 modeling exercises, which are intended to assess a high-transit deployment scenario, reflect forecasted regional growth of over 4 million new residents and over 1.5 million more jobs between now and the year 2045. The forecasts take into consideration development patterns, prices of land and types of housing selected across the demographic spectrum and spread throughout the region. **Figure 14** illustrates how approximately 20% of the new residents moving into region between now and 2045 will choose to live in and around the Urban Core and 80% will move into the suburban and exurban rings of the region outside Beltway 8 – primarily along the western and northern edges.

While the growth of employment concentrations is anticipated to increase significantly around the edges of the region, the highest concentration of jobs will remain within the urban core. This reality is what drives the need to provide increasing transit services and dramatically more transit capacity in order to carry the majority of workers' morning commute trips from the edge of the region where they live into the urban core where they work, and then back to the regional edges during the evening commute period.

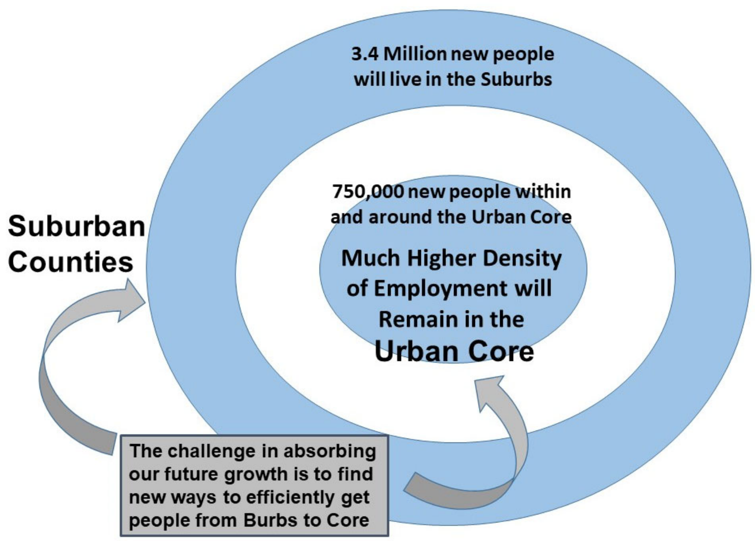


Figure 14 Distribution of Houston's Growth Between 2018 and 2045

The results of the modeling of an extensive transit system network and the corresponding transit ridership forecast for this conceptual transit deployment scenario has been referred to as the H-GAC 2045 HCT Vision Plan. The HCT Vision Plan network is shown in **Figure 15A** and a graphical representation of the associated 2045 HCT ridership forecast is shown in **Figure 15B**.

This network incorporates the METRONext plans for Harris County, and it adds/extends substantial transit service throughout the other seven counties covered by the H-GAC Regional Transportation Plan. A summary of the ranking of the main corridors by ridership activity levels is provided in **Table 2**. This theoretical transit ridership pattern provides an important definition of the relative transit use (or at least relative transit demand) that could be expected in each of the major corridors when very high transit system capacity and connectivity are provided. It should be noted that a more detailed analysis of each corridor will be required through subsequent corridor studies in order to provide the final determination of an actual transit ridership forecast appropriate for use in the official Regional Transportation Plan.

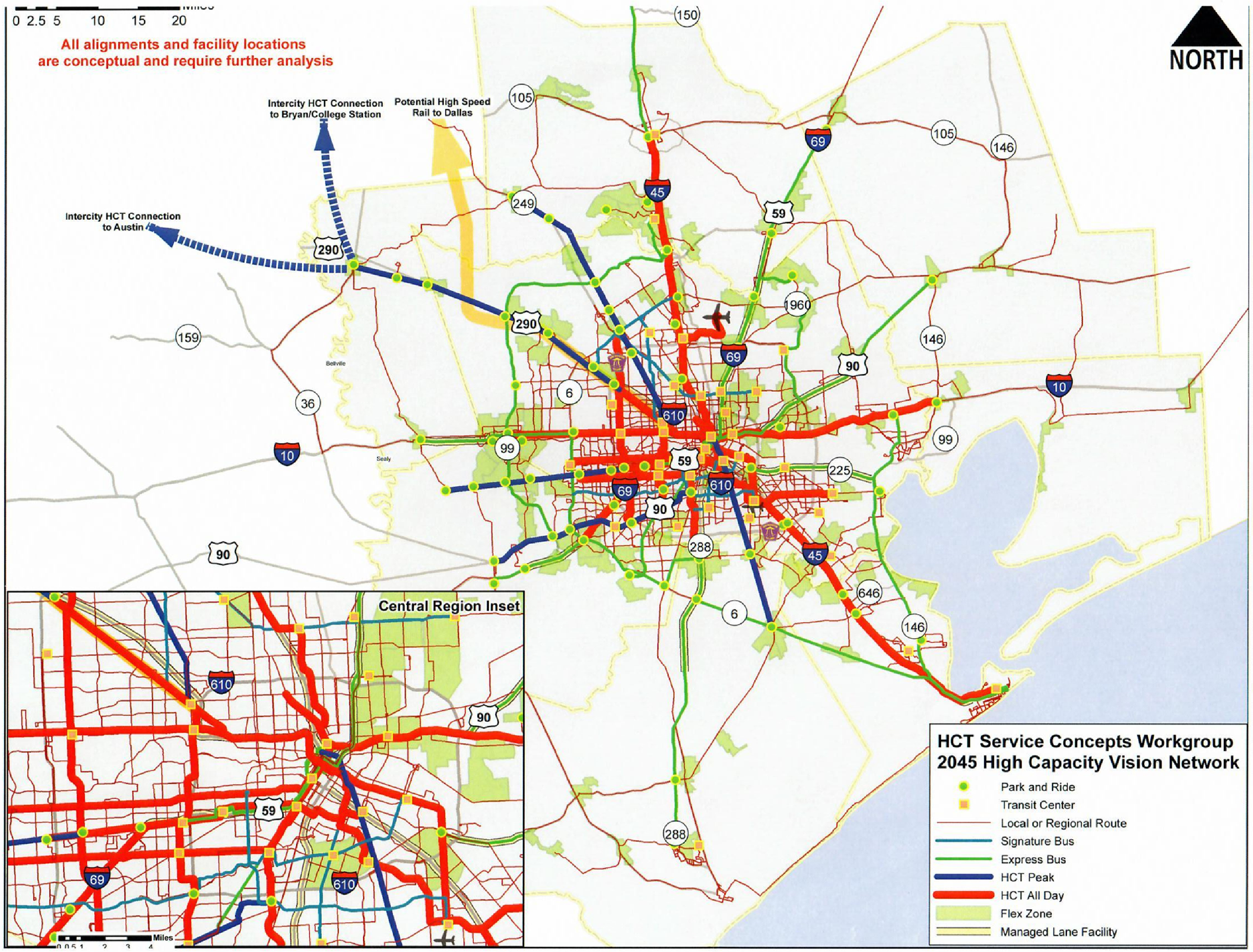


Figure 15A H-GAC 2045 High Capacity Transit Vision Plan Network

For purposes of this conceptual ridership analysis, each corridor and Service Concept has been assumed to have unlimited capacity.

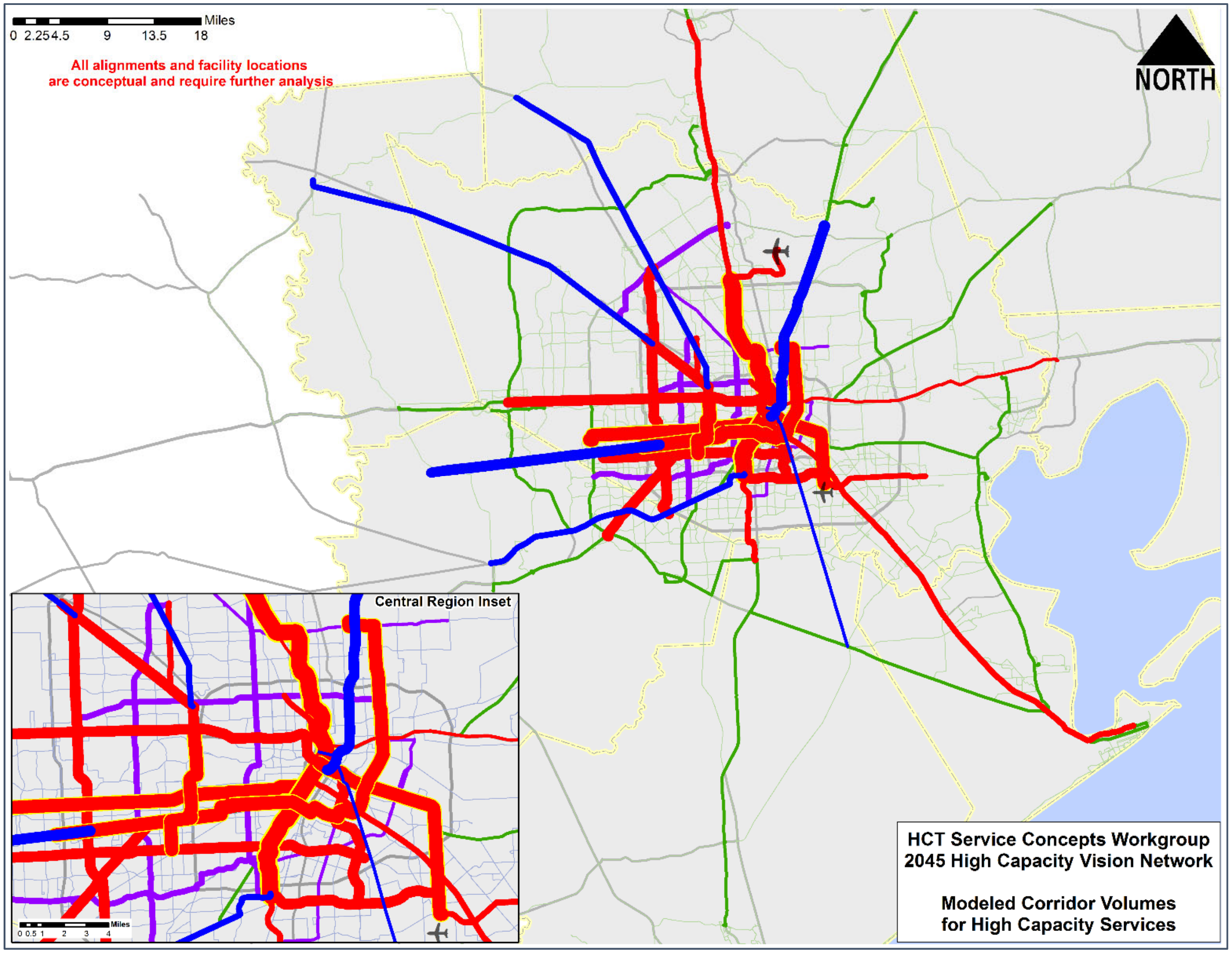


Figure 15B H-GAC HCT 2045 Vision Plan Preliminary Forecast of Relative Link Demands

Thickness of segments indicates relative demand in terms of transit passenger ridership volumes.

All alignments are conceptual in nature and require further analyses

Table 2 Ranking of 10 Highest Demand Corridors from 2045 HCT Vision Plan

Corridor	Type of HCT Service (All Day, Bi-Directional)	Total Daily Boardings	Length (Miles)	Daily Boardings Per Mile
Westpark/Richmond/Lockwood – From Westchase to Tidwell Transit Center	Subregional Corridor	282,385	26.4	10,680
Main Street/North Red Line LRT – From Greenspoint District to Fannin South P&R	Subregional Corridor	259,821	21.6	12,018
Westheimer – From West Oaks to Downtown	Subregional Corridor	171,170	18.6	9,227
East End/Green Line LRT – From Downtown to Hobby Airport	Subregional Corridor	119,384	10.9	10,983
Gessner/West Belt – From Willowbrook Mall to Missouri City	Subregional Corridor	89,970	25.0	3,593
Inner Katy – From Northwest Transit Center to Downtown	Subregional Corridor	87,222	6.5	9,201
Bellaire – From Mission Bend P&R to Palm Center Transit Center	Subregional Corridor	83,056	19.8	4,186
Post Oak – From Northwest Transit Center to Gulfton Transit Center	Subregional Corridor	68,236	7.0	9,776
Hempstead Highway – From West Little York P&R to Northwest Transit Center	Subregional Corridor	51,284	6.3	8,140
East Bellfort – From Fannin South P&R to Hobby Airport	Subregional Corridor	30,229	8.9	3,397

NOTE: These forecasted numbers are based on highly aggressive and hypothetical parameters, including the demand assignments to transit lines without any design constraints (such as capacity limits due to vehicle size, maximum train consist or bus platoon length, or minimum headways). These ridership levels may change as H-GAC continues to refine and analyze the 2045 Vision Plan.

The discussion that follows addresses the general implications of this level of transit ridership for transit system technology and facilities, as well as a conceptual look at connectivity within the urban core.

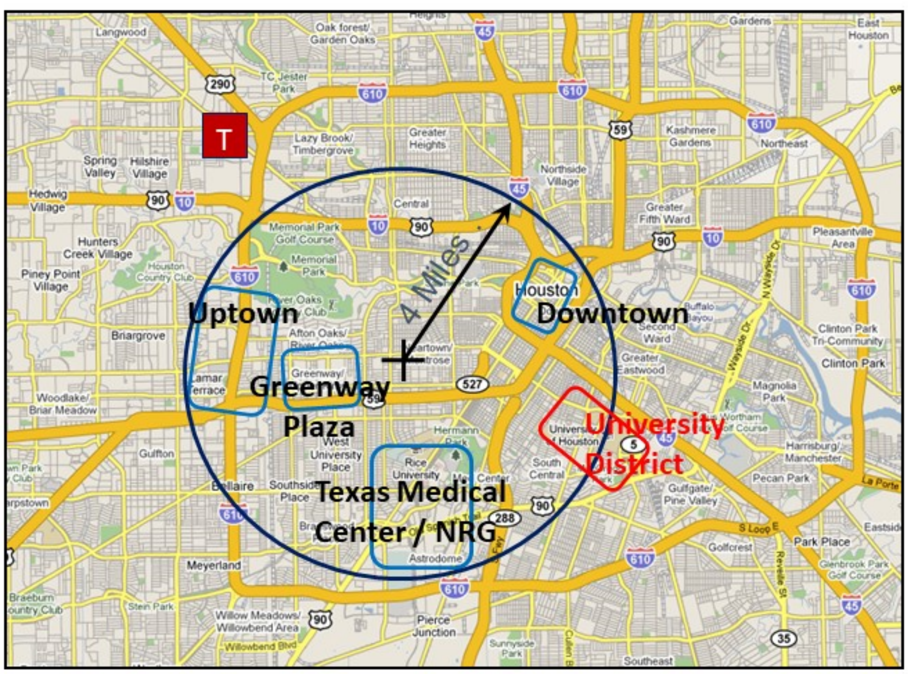
3.1 Connected Corridors, Districts and Town Living Centers

The proliferation of master planned communities around the exurban edges of Houston – which then evolve into the new ring of suburban small towns and "town centers" – has shown that residential development truly has reshaped the landscape from the more historic growth patterns that progressively grow out from the urban core. The excellent system of radial freeways and tollways have made the combination of cheap land and master planned communities into a wonderful lifestyle scenario which combines small town living far from the urban core with big city jobs in the center of the region. This development pattern has resulted in major travel corridors connecting between remote suburban towns and living centers, and central city major activity centers and urban employment districts, thereby driving the trip generation during the most congested periods of the day. What will compound this challenging development pattern is the sheer quantity of new Houstonians that are forecasted to live in this suburban/exurban ring, as illustrated above in **Figure 14**.

Work related trips moving through our system of "hub and spoke" travel corridors that connect town centers with employment districts will remain the most challenging trips to serve, even as AV technology transforms both our personal automobiles, the new ride-hailing car services, as well as the public transit vehicles and systems. Studies continue to indicate that traffic congestion in general will be increasing rapidly as a result of our massive growth (refer to **Section 1.0**). As a result, there is continued development in more and more major employment centers around the edges of the region.

Newly developing urban districts and major activity centers are beginning to thrive around the Beltway and beyond. However, the fact remains that the largest concentration of employment centers that must be served through HCT systems and infrastructure will continue to exist within the area encircled by IH-610.

Figure 16 shows an area which is defined as the specific "Urban Core" for purposes of this paper. This Urban Core is formed by a 4-mile radius area around and within IH-610 Loop to the south and west of Downtown. This concentration of major employment centers comprises Downtown (150,000 daily commuters), Uptown/Galleria (130,000 daily commuters), Texas Medical Center/NRG Park (100,000 daily commuters[10]) Greenway Plaza (70,000 daily commuters), and the University District (50,000 daily commuters), in which "daily commuters" in an approximate metric that indicates "inbound" person-trips that have a potential for HCT travel mode choice. This approximation of person-trips coming into the Urban Core area totals in the order of 500,000 daily commute trips, a majority of which are traveling from the edge of the region into the dense concentration of districts and major activity centers around and within Loop IH-610.



Houston's Urban Core Within Loop I-610 contains the University District Plus Four Urban Districts Which are Major Employment Centers*

* Each Urban District (if it were classified as a CBD) would be large enough to be on the list of the 15 largest CBDs in the U.S.

Source: Google Earth

Figure 16 Concentration of Major Urban Districts Within the Urban Core

10 TMC's daily "commuters" include employees, patients, visitors and students.

When new high capacity transit services are applied with a scale suitable to address this dramatic increase in the number of people traveling between the suburbs and the Urban Core each day, there will also need to be new means to provide for circulation within the Urban Core. This new means for access into each of the major employment districts requires "last-mile" connections from the closest HCT intermodal station located in proximity to the district. Similarly, mobility within each employment district will require a means of circulation within the district. **Figure 17** illustrates this new type of transit functionality proposed in past studies (reference **Figure 10**) with fully automated transit operating on grade-separated transitways running above the traffic congestion, and with strategic transition points allowing automated vehicles to also reach the at-grade street network to operate in mixed traffic. As shown in the figure, efficient connections with perimeter parking, conventional at-grade transit, and high capacity transit (both Regional Express and Subregional Corridor service) are provided in this conceptual plan.

It is within this Urban Core that densification of housing development is also occurring at an unprecedented pace, and traffic congestion along city streets is growing at a rate comparable to the congestion of the freeways within the core. Rising land prices in the Urban Core are increasingly adding fuel to the factors that drive housing densification, with new development offering medium and high-rise residential living in a mixed-use context.

All of these factors add urgency to the consideration of how to tie together all existing and future HCT services carrying passengers into and out of the very large urban districts and major activity centers within the Urban Core. It is clear that a suitable circulation and distribution system is needed which will provide a first-mile/last-mile connectivity essential for HCT to succeed to the level needed. Furthermore, when transit mode travel demands reach the levels forecasted (see **Table 2** above), meeting the objective of providing efficient mobility with high capacity transit will require new, grade-separated transit infrastructure to be created. This new infrastructure will facilitate circulator systems with FM/LM functions, as illustrated in **Figure 17,** becoming a critically important part of the region's overall transportation plan.

Figure 18 illustrates how the concept of Regional and Subregional Corridor HCT must should be created to carry passengers between the distant town-centers, suburban districts located around the perimeter of the region and into the urban districts located within the Urban Core. In each district, connections to the AV Microtransit circulation systems should be convenient and accessible. This integrated and connected transit system will be able to provide legitimate options to travel by automobile for long distance and moderate distance trips across the region.

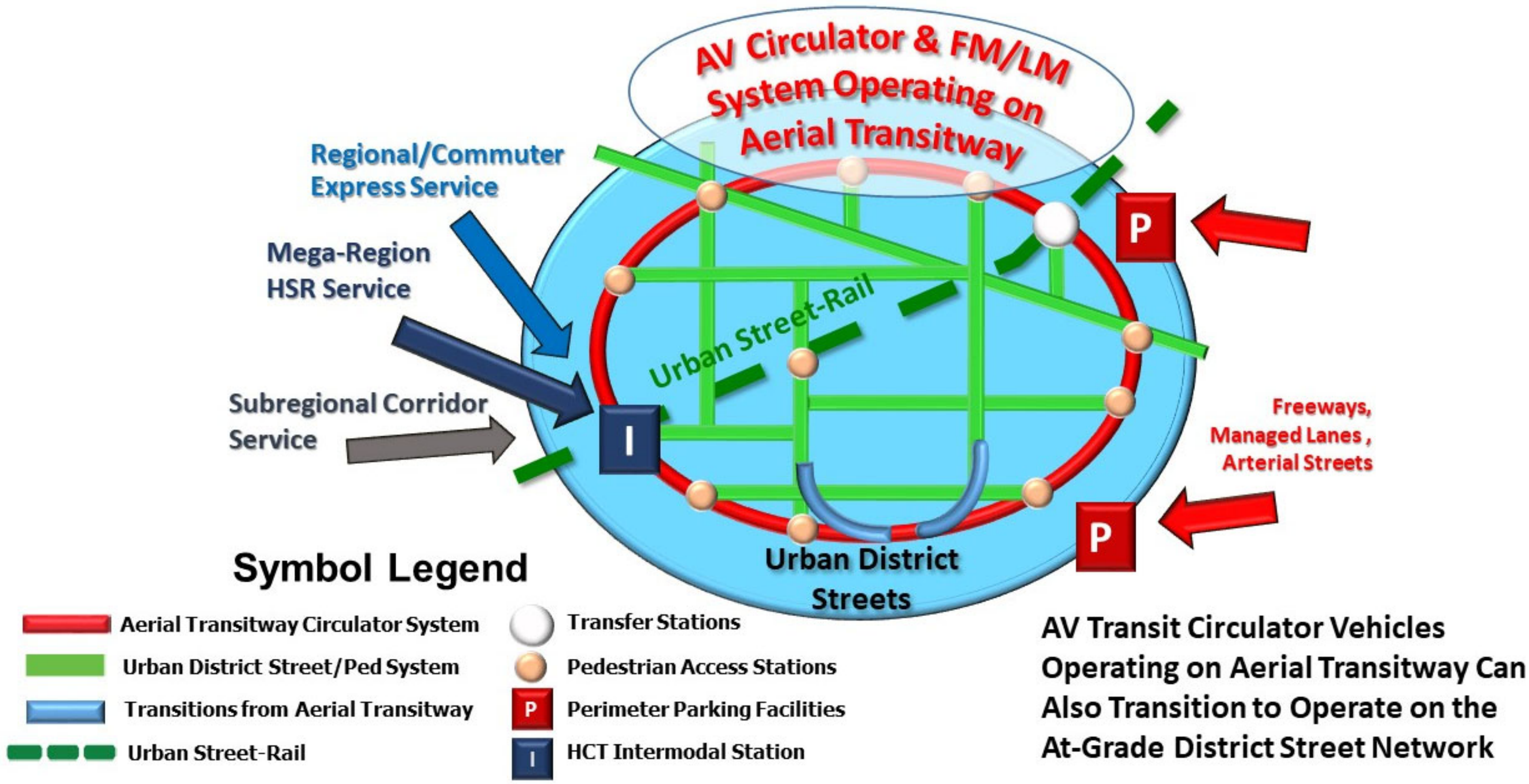


Figure 17 Aerial Circulator Transitway Concept to Provide Circulation and FM/LM Connectivity to High Capacity Transit and Street-Level Local Transit Systems

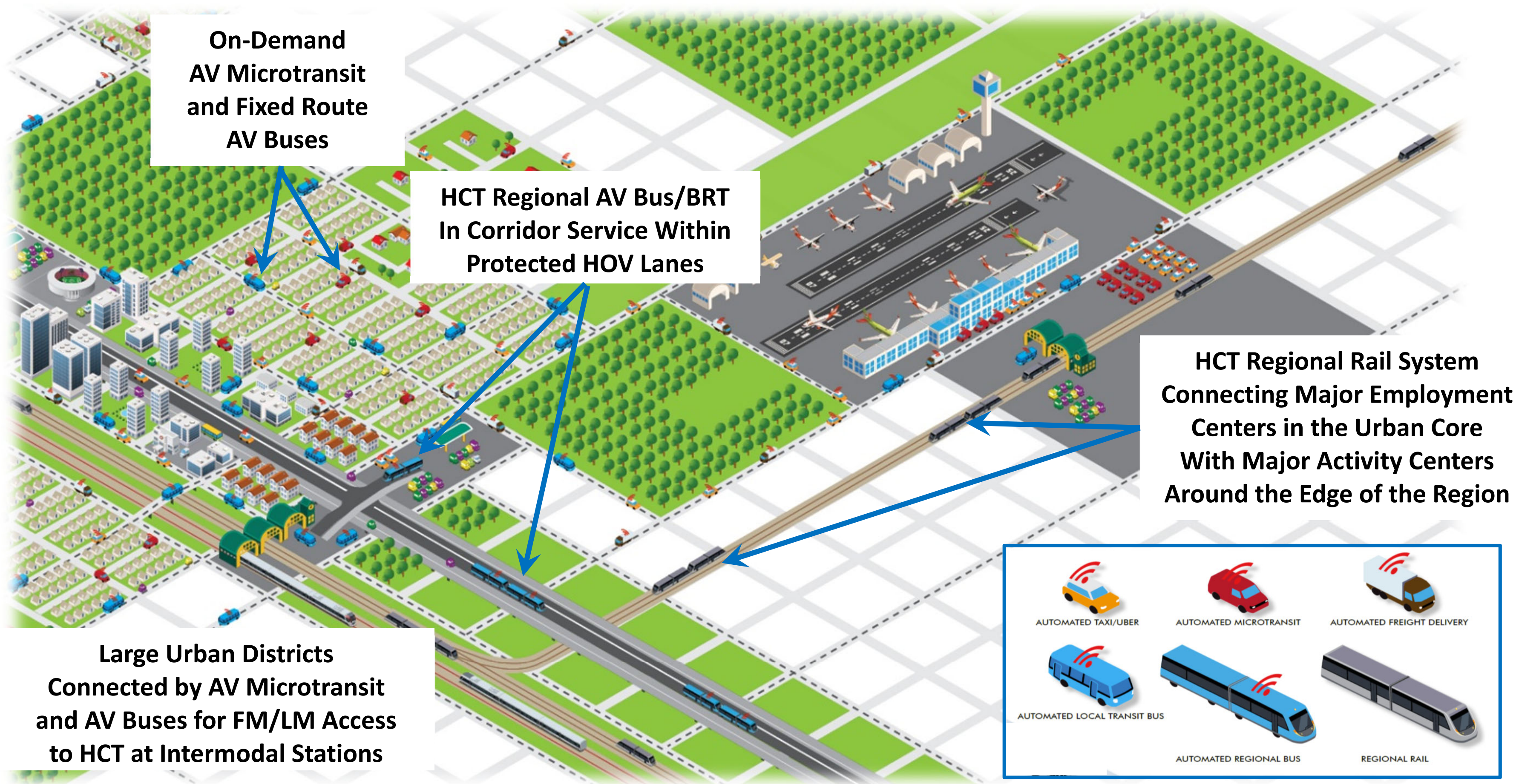


Figure 18 Multimodal Subregional and Regional High Capacity Transit Services All Connect at Major Business District Intermodal Stations

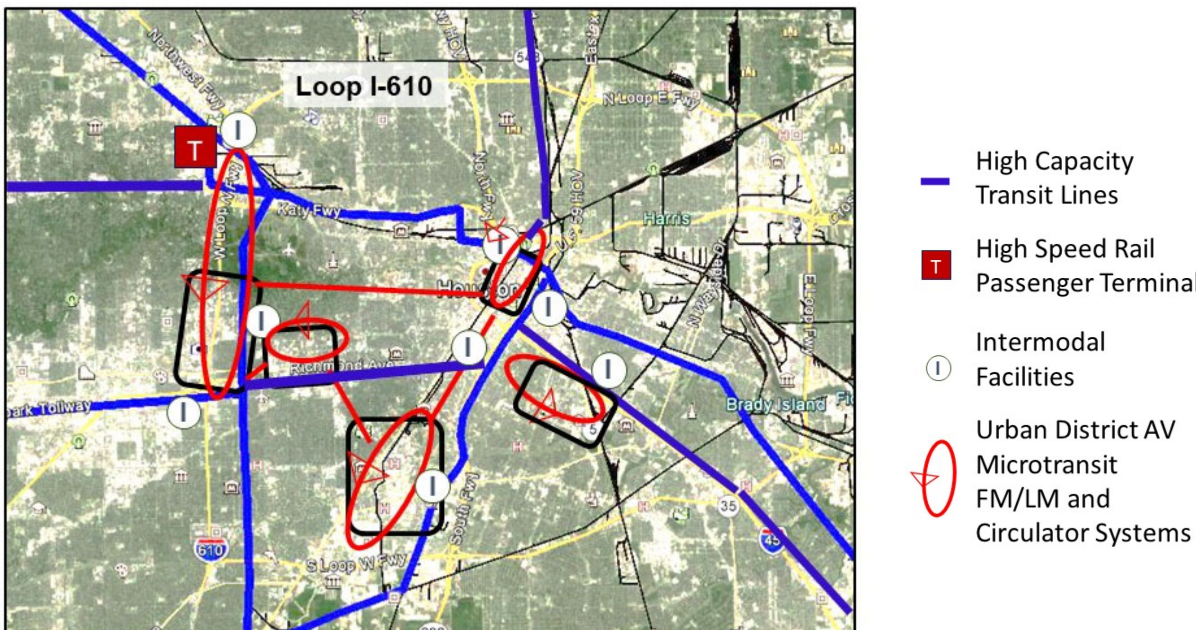
Source: Houston-Galveston Area Council

3.2 Circulation and Connectivity in Houston's Urban Core

The Houston Region has an unusually dense concentration of major urban districts in close proximity to each other within the Urban Core. **Figure 16** above depicted the four very large and closely-spaced employment and activity centers which have a rapidly growing residential population within the surrounding Urban Core, as well as a fifth major activity center formed by the cluster of U of H and TSU university campuses – described above as the University District.

Figure 19 shows a concept for Urban Core circulation and FM/LM connectivity to HCT using a wholly new, advanced technology AV Transit system network – primarily for circulation trips within each of the major districts (see **Figure 17** above). Then with the addition of interconnecting transitway linkages, express service between the major districts can be provided. The current systems of at-grade local bus transit and LRT services will still be needed to move the majority of residents who live within the urban core to/from destinations in and around the major districts where access to the new grade-separated systems would be possible. This concept of grade-separated transitways for FM/LM connections and urban district circulation connecting to large metropolitan rail system has precedent in several international cities of the world, including Miami and Singapore. See the case studies of these examples in **Appendix C**.

NOTE: This is a conceptual illustration, and is not intended to show HCT alignments currently planned by H-GAC.



Source: Google Earth

Figure 19 Linking of Urban District Circulator Systems with Express Service Would Create a Unified "CBD" Through the Interconnection of All Districts Within the Urban Core

The number of transit riders on All Day Service that would be flowing into the Urban Core in combination with peak hour Regional Express commuter service is extremely large in the 2045 HCT Vision forecast, and will require major investments in the new advanced technology infrastructure and systems dedicated to first-mile/last-mile service. As a closer view of the urban core from the regional transit ridership shown above in **Figure 15**, the comparative scale of ridership demand for the various corridors within the Beltway is shown in **Figure 20** below.

Table 3 gives the 2045 HCT Vision Forecast modeling results of daily boarding activity at a few of the highest activity stations. Note that as of the date of this Opinion Paper's release, H-GAC is in a preliminary

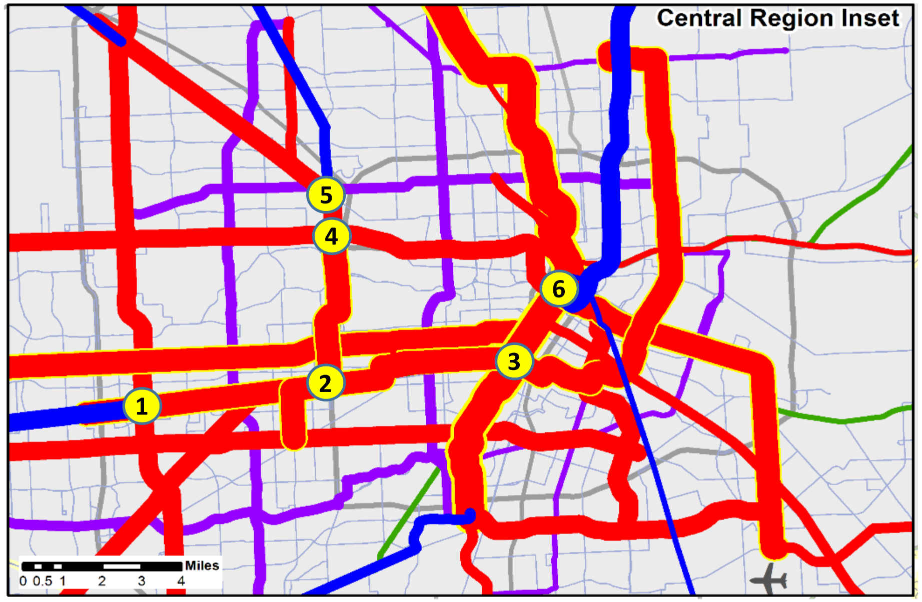


Figure 20 2045 HCT Vision Plan Preliminary Forecast of Transit Ridership Within the Center of the Region

All alignments and station locations are conceptual in nature and require further analysis

Table 3 2045 HCT Vision Plan Preliminary Forecast of Daily Passenger Boarding Activity at the Most Active Intermodal Stations

Westpark/Richmond HCT Line	**Uptown/Post Oak HCT Line**
1. Westchase District Intermodal Station – 157,621 Boardings ○ Includes transferring passengers from Westpark/Richmond, Gessner/West Tollway, and Outer Westpark commuter lines 2. Bellaire/Uptown Transit Center – 26,111 Boardings ○ Includes transferring passengers from Westpark/Richmond and Uptown/Post Oak Lines 3. Wheeler/Blodgett Transit Center – 24,928 Boardings ○ Includes transferring passengers from Westpark/Richmond and Red Line LRT	4. NW Transit Center – 46,722 Boardings ○ Includes transferring passengers from Inner Katy and Outer Katy Line 5. HSR Terminal – 8,117 Boardings ○ Includes transferring passengers from Hempstead HCT line, but not Texas Central HSR Line **HCT Red Line** 6. Downtown Central Station – 20,524 ○ Includes transferring passengers from HCT Green Line and HCT Purple Line

NOTE: THE VALUES IN THIS TABLE WERE UPDATED ON MARCH 26, 2019. Ongoing studies by H-GAC are in progress which are refining and analyzing this preliminary data. However, conclusions drawn from this preliminary data in this Opinion Paper are general in nature and broad in perspective.
The results of this forecast are based on high frequency of service and aggressive assumptions of HCT Line capacity.

phase of analyzing these intermodal station activity levels and their associated patterns of connecting transfers between the multiple corridors and transit lines. Further insight will be gained through H-GAC's continuing analytical process as to how connections between corridors/lines can have the passenger loads distributed and optimized. As these H-GAC studies continue, the values of boarding activity will change from those shown in Table 4. But what can be definitely asserted from the preliminary numbers is that serving these levels of ridership will overwhelm the currently existing at-grade transit systems. This fact gives substantial weight to the importance of carefully preparing for an extensive and efficient high capacity transit system that is separated from traffic wherever possible, thereby allowing a high frequency of service and a resulting higher capacity. Therefore, providing express service connectivity between the major employment centers and business districts, in addition to the basic first-mile/last-mile service and circulation within each of the major districts, could provide the additional transit capacity needed to serve the forecasted ridership demands within the Urban Core.

Furthermore, the extremely large size of the preliminary boarding numbers for the several intermodal stations which have forecasted station activity in **Table 3** clearly indicates that the scale of the intermodal station facilities is far beyond what has been envisioned within the Urban Core. Comparing the boarding level's shown in the table with METRO's highest level of current transit station boarding activity illustrates this point. The TMC Transit Center has the highest combined bus and rail daily boarding activity of all the stations within the current METRO system, with TMC typically seeing about 3,000 rail and 6,000 bus average boardings on a typical weekday. This reference point of 9,000 to 10,000 boardings on a typical day at TMC compares to 2 ½ times that level of boarding activity at the future Wheeler/Blodgett Transit Center Station for the 2045 HCT Vision Plan forecast of ridership on the conceptual system. The boarding activity forecast for the Northwest Transit Center in 2045 is over 4 ½ times greater, and the boarding activity at the Bellaire/Uptown Transit Center is forecast to be 2 ½ times greater than the current boarding activity at the TMC Transit Center.

Urban Core Transitway System – The creation of a connected and integrated multimodal system within the urban core is absolutely essential to a future which includes HCT access and overall mobility. To accomplish this future objective the concept of creating a grade-separated transitway system for AV Microtransit and AV Bus circulation is proposed in this Opinion Paper as a key element of this HCT future. Although the new AV Microtransit and full size AV Buses are still in prototype form, it is not difficult to understand how this technology can be operated in a fully automated operation to carry transit passengers to and from HCT Intermodal stations and within major urban districts.

As mentioned above, **Appendix C** provides several examples of other cities which have created fully automated circulation and FM/LM transit systems within their largest urban districts, with FM/LM connections to high capacity transit lines operating in regional and subregional corridor service. **Appendix C** also provides insight into the benefits of the type of grade-separated transitway that will be needed within the urban core of Houston by the time the forecasted 2045 HCT Vision Plan transit activity would be reached.

This conceptual transitway that is proposed as a grade-separated system with an aerial alignment will be referred to in this paper as the Urban Core Transitway System, as shown in the **Figure 21** photographs of a transit circulator and FM/LM system now deployed in several major districts of Singapore (see a discussion of this system in **Appendix C**).

There is another relevant example of this concept of an aerial transitway configuration that is being designed for AV Microtransit technology is described in **Appendix C** as an application which will include operations along both at-grade roadways and on elevated transitways. This example of transit infrastructure which is directly comparable to the proposed Urban Core Transitway System for Houston has been described by Jacksonville Transportation Authority (JTA) in their plans to create the Ultimate Urban Circulator (U^{2}C) system. **Figure 22** has a rendering prepared by JTA which illustrates the concept for the transition of the aerial transitway to an at-grade transitway.

Figure 21 Automated Transit Circulator System Providing FM/LM Service Along an Aerial Transitway In the Sengkang and the Punggol Districts of Singapore

Figure 22 Illustration of JTA's U^{2}C Transitway Transitions from Aerial to At-Grade Segments
Illustration used by Permission of: Jax Transit Innovation Corporation (JTI)

A significant benefit of creating this Urban Core Transitway System is that the automated buses operating along the freeway corridor HOV system could conceivably continue their travel along the portions of the transitway that are designed for this full size vehicle. With direct connections between the HOV transit ways and the Urban Core Transitway System, a transit user could travel from a remote location (such as the Cypress Park & Ride) to a location within the Urban Core (such as the TMC Transit Center) with a one seat ride on a large automated bus that could potentially bypass all intermediate stations. The passenger could then transition to either the Red Line LRT or to a small AV Microtransit vehicle to complete her trip within the Texas Medical Center – such as to a final destination at the MD Anderson Cancer Center.

Off-Line Stations – Configuring the Urban Core Transitway System with primarily "off-line" stations along portions of the alignment – such as shown in **Figure 23** – is an important design feature allowing service for all sizes of AV transit vehicles. Much like the current design of transit centers off-line from the HOV lanes (see **Figure 4 and 9** above), the creation of off-line stations can accommodate direct point-to-point service between any two stations without affecting other transit vehicles traveling along the main transitway through-lanes.

Source: Wikimedia, and: http://www.expo2005.or.jp/en/technology/imts.html)

Figure 23 Example of an Off-Line Station for Toyota IMTS Buses Deployed at the 2005 Transportation Expo in Aichi, Japan

The opportunity exists to combine point-to-point service between major origin and destination stations for all large and small vehicles on the Urban Core Transitway System, if off-line station configurations are included. Then when combined with on-demand dispatching of AV Microtransit vehicles, the automated system will enable both the AV Bus service and the AV Microtransit service to be flexible, with operations satisfying FTA's concept of Mobility-on-Demand. As discussed above, this operating concept with demand-response dispatching of vehicles in real time, is also called ATN operations.

For a more technical discussion of off-line stations and the flexibility of operating concepts that are facilitated by these station configurations, see **Appendix D** which contains an excerpt from a technical paper[11] published in the proceedings of an international conference on fully automated transit systems.

[11] *Preparing for Automated Roadway Technology Impacts on Guideway Transit;* J. Sam Lott and Douglas Gettman, PhD, ASCE International Conf. on APMs and ATS; Toronto, April 20, 2016

3.3 Strategic Locations and Configurations for HCT Intermodal Facilities

For this new transit paradigm to work well, there will need to be stations where many people transition between travel modes at strategic locations in direct proximity to each of the major urban districts and major activity centers. For example, a traveler leaving a district office building would board a district FM/LM circulation system, travel to a nearby intermodal facility to transition to HCT service and continue their travel to the edge of the region along a specific travel corridor. Similarly, a person traveling to the urban district from another smaller district along the corridor would transition to the FM/LM system to reach their residential tower nearby, or exit the facility to continue to an adjacent transit oriented development (TOD) development as a pedestrian.

Although basic travel mode transitions occur at all station locations, in those key locations where these transfers occur at a very high level of activity there must be a special class of station facilities – designated herein as intermodal stations. In particular, there is a need for this type of special intermodal facility at strategic locations where HCT services interconnect – such as a station serving multiple different rail lines, where AV buses from multiple travel corridors will access the station site via direct connector transitways from nearby HOV lanes, or combinations of different HCT modes come together at one location.

There have been several past studies of intermodal station facilities for high capacity transit in Houston, particularly with respect to intermodal stations that would serve multiple commuter rail lines at locations in or directly adjacent to Downtown Houston[12]. Proceeding these focused CBD studies was a prior study that looked at a major intermodal rail station along IH-610 West Loop between IH-10 and US 290. This site was proposed in the 2009 H-GAC Regional Commuter Rail Connectivity Study as the optimal location of a major operational hub terminal for a regional commuter rail system[13]. All of these past studies performed over the past decade provide insight into the intermodal facilities that will be required for the new paradigm of HCT as conceptually defined in the 2045 Vision Plan – both for rail systems and AV Buses operating along the freeway HOV system.

In addition to the need for a major intermodal station(s) near Downtown Houston, there are other intermodal station sites that that are currently being developed in the planning for both Subregional Corridor and Regional/Mega-Regional service. Examples of these are the Bellaire/Uptown Intermodal Station planned for the south end of the Uptown/Galleria BRT Line and the HSR Terminal currently being considered for construction at the Northwest Mall site (which is an alternative site to the commuter rail hub terminal between IH-10 and US290 mentioned in footnote 13).

At the current time as part of the METRONext planning effort, a large transit center has also been identified with the scale and HCT service combinations that would qualifying it as a "strategic" intermodal facility. This location is the Wheeler/Blodgett Transit Center at the south end of Midtown where the

[12] Two studies were conducted simultaneously and collaboratively by METRO and H-GAC in 2010, each addressing alternative sites for a major Downtown Houston Transit Intermodal Station. No specific site selection was made, pending further studies. One of the study reports was titled "Downtown Houston Transit Intermodal Station – 2010 Update to Site Location Assessment."

[13] In 2009 a "Regional Commuter Rail Connectivity Study" was led by Kimley-Horn and Associates, with HNTB and Fregonese Assoc., and performed under the auspices of H-GAC. The assessment of alternative sites for an "operational hub terminal" suitable to serve as the terminus of a number of regional commuter rail lines resulted in the recommendation of a site immediately west of the West Loop freeway. Ridership studies were performed by Wilbur Smith Assoc. as part of the study team.

METRO Red Line LRT crosses IH-69 -- within which HOV lane connections have also been suggested for further study. Further, this facility would be located right in the middle of the conceptual Urban Core Transitway System discussed in the preceding subsection and illustrated in **Figure 19** above. This particular intermodal facility is anticipated to be of strategic importance as HCT concepts for an interconnected system are developed further over the course of time.

Certainly other sites along the outer perimeter of the region, particularly at locations where major activity centers and urban districts are developing will also need consideration for an intermodal facility. As indicated by the scale of transit boarding/alighting activity that is shown in **Figure 20** above, intermodal facilities along the Beltway 8 corridor where east/west HCT corridors cross a north-south HCT line should also be studied.

But for purposes of this paper, the strategic locations within the Urban Core within and around IH-610 Loop have a focused discussion below.

Strategic Intermodal Facilities within the Urban Core – All of the intermodal facilities considered here are of potential strategic importance for serving an integrated and connected multimodal HCT system. Each site will be briefly discussed below, followed by a discussion of the implications for intermodal station configuration when the new AV Transit technologies become part of the transit mix for Subregional Corridor and District FM/LM service.

Figure 24 shows the HCT intermodal station sites that have been studied in the past or are currently in development within the Urban Core. Each of these should be considered for further development as a part of a concept for HCT connectivity within the Urban Core.

Figure 25 is taken from the 2010 Downtown Houston transit intermodal station site assessment study (see footnote 12.) to illustrate the theoretically optimum site for maximum accessibility as a pedestrian, compared to the three sites around Downtown which were considered to be accessible by passenger rail at that time. This figure clearly illustrates that the Downtown District is too large to be accessible as a pedestrian from a single location, and therefore some type of circulation system is warranted for FM/LM transit service no matter where the high capacity transit intermodal station would be located.

For that reason, the 2010 study included a description of a conceptual Downtown Aerial Guideway Circulator System Concept. A dedicated appendix of the report addressing this concept included photos and drawings from the aerial segments of the Copenhagen Metro system – a fully automated rail system that has been in service for over 15 years.

The ***Burnett Plaza/Hardy Yard Site*** is located on the Union Pacific "Freight Main" where METRO has owned a substantial amount of property and has even performed architectural design studies of a major intermodal facility at this location. However, UP has never been willing to consider the operation of passenger trains along this segment of the railroad network. The site has been developed, however, as a significant multimodal transit center on the Red Line LRT as a transfer hub for multiple bus lines.

In comparison, the ***Post Office Sit***e has also had multiple studies performed of using this location for a major intermodal rail station. This is in part because it is located on the portion of the railroad network called the "Passenger Main", and since it is the location of the current Amtrak Station with a train yard that remains from the original Houston Passenger Rail Terminal in operation a century ago.

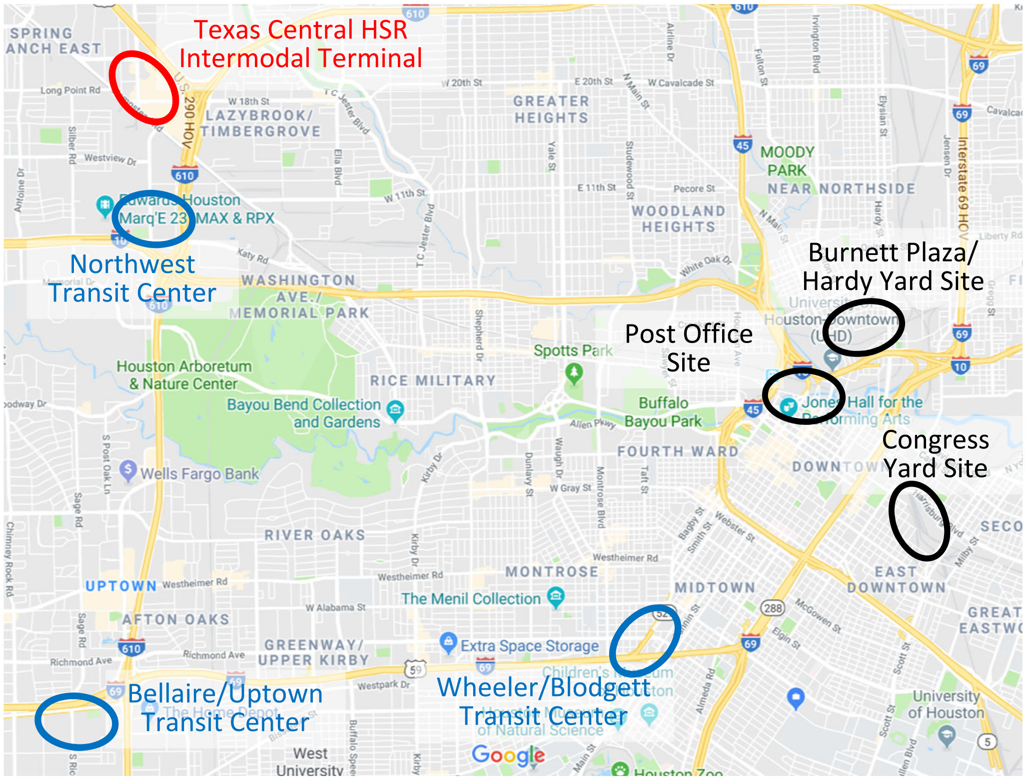


Figure 24 Strategic Locations to be Considered for Transit Intermodal Station Placement Within the Urban Core

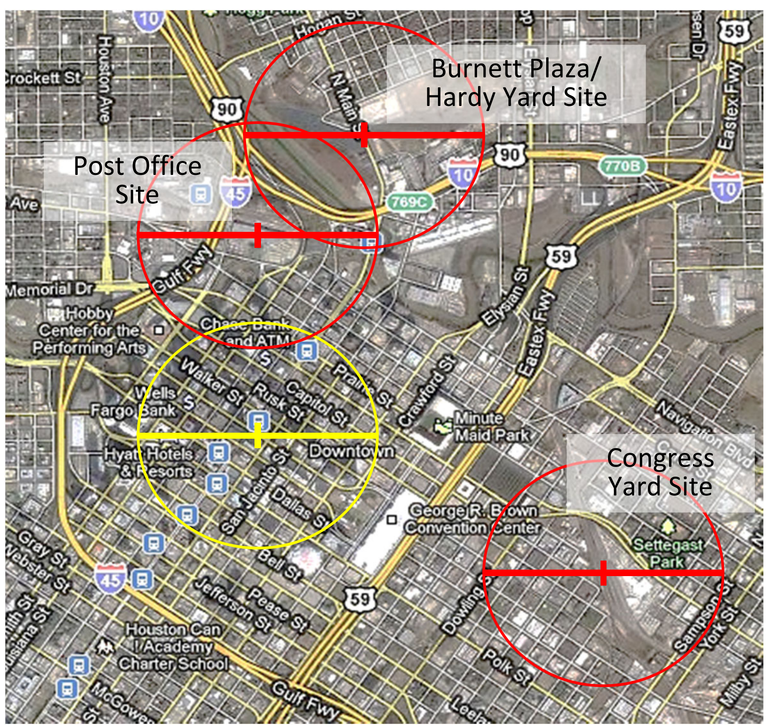


Figure 25 The "Theoretically Optimal" Site Location (yellow) for Practical Walking Access to the Majority of Downtown Destinations Compared to Three Alternative Intermodal Station Sites (red)

Source: H-GAC and Kimley-Horn and Associates, Inc.

Figure 26 (2 pages) is taken from a 2012 TxDOT study of a statewide high speed rail system, and the Post Office Site land area was assessed for a large station serving HSR, intercity passenger rail, regional commuter rail, as well as intercity and regional bus operations. However, the site has been sold and the development plans for the land and whether any remaining suitability exists for constructing a large station are unknown.

However, both the Burnett Plaza/Hardy Yard Site and the Post Office Site may still be very good locations for placement of a HCT AV Bus intermodal facility due to their proximity to the convergence of IH-10, IH-45 and IH-69 on the north side of Downtown. This entire freeway interchange is currently being redesigned by TxDOT, and the opportunity to provide direct connectors to either potential site from HOV lanes within these freeways could be investigated in light of the new freeway relocation along the north side of Downtown. Investigation of land availability at either site for such a HOV Bus System Intermodal Facility is recommended for discussion with TxDOT and associated agencies/developers.

Congress Yard Site also remains a potential for an East Downtown intermodal facility serving passenger rail, with access connections easily provided to both the METRO Purple (Southeast) and Green (East End) LRT Lines. This is considered a very good location to provide passenger rail access to Downtown and the Urban Core, particularly from the southern part of the region. For example, a commuter rail line that has been long envisioned for service along the Texas State Highway 3 / IH-45 South corridor to Galveston connects directly to this site.

Other HCT transit lines that could be implemented as passenger rail lines connecting to the Congress Yard site are shown in the 2045 HCT Vision Network (see Figure 14 above) – such as in the State Highway 35 corridor, which parallels the Mykawa Subdivision passing through both Pearland and Alvin.

Another passenger rail line serving the southwest part of the region operating along the UP Glidden Subdivision railroad and which could conceivably connect to the Congress Yard site has been studied over the last decade by both H-GAC and most recently by the Gulf Coast Rail District[14]. Known as the 90A Commuter Rail Line in the past studies, this passenger rail line would operate through the US 90A corridor to connect the Texas Medical Center with the cities of Sugarland, Richmond and Rosenberg and potentially continue across Fort Bend County to the western border with Colorado County. Within the Urban Core, this 90A passenger rail line could conceivably turn north from the UP Glidden Subdivision railroad to reach a proposed station on the Columbia Tap railroad spur adjacent to Almeda Road – a good location for a major intermodal station serving the Texas Medical Center/NRG District. Some consideration has also been given to connecting from this TMC intermodal station site with an extension north to the vicinity of Congress Yard, potentially on an alignment that generally follows the US 288 Freeway corridor.

[14] Regional Commuter Rail Feasibility Study – An Assessment of Right-of-Way, Track Alignment and CBD Access; prepared in 2015 for the Gulf Coast Rail District by the engineering team led by Kimley-Horn, with TranSystems, Quadrant and Knudson.

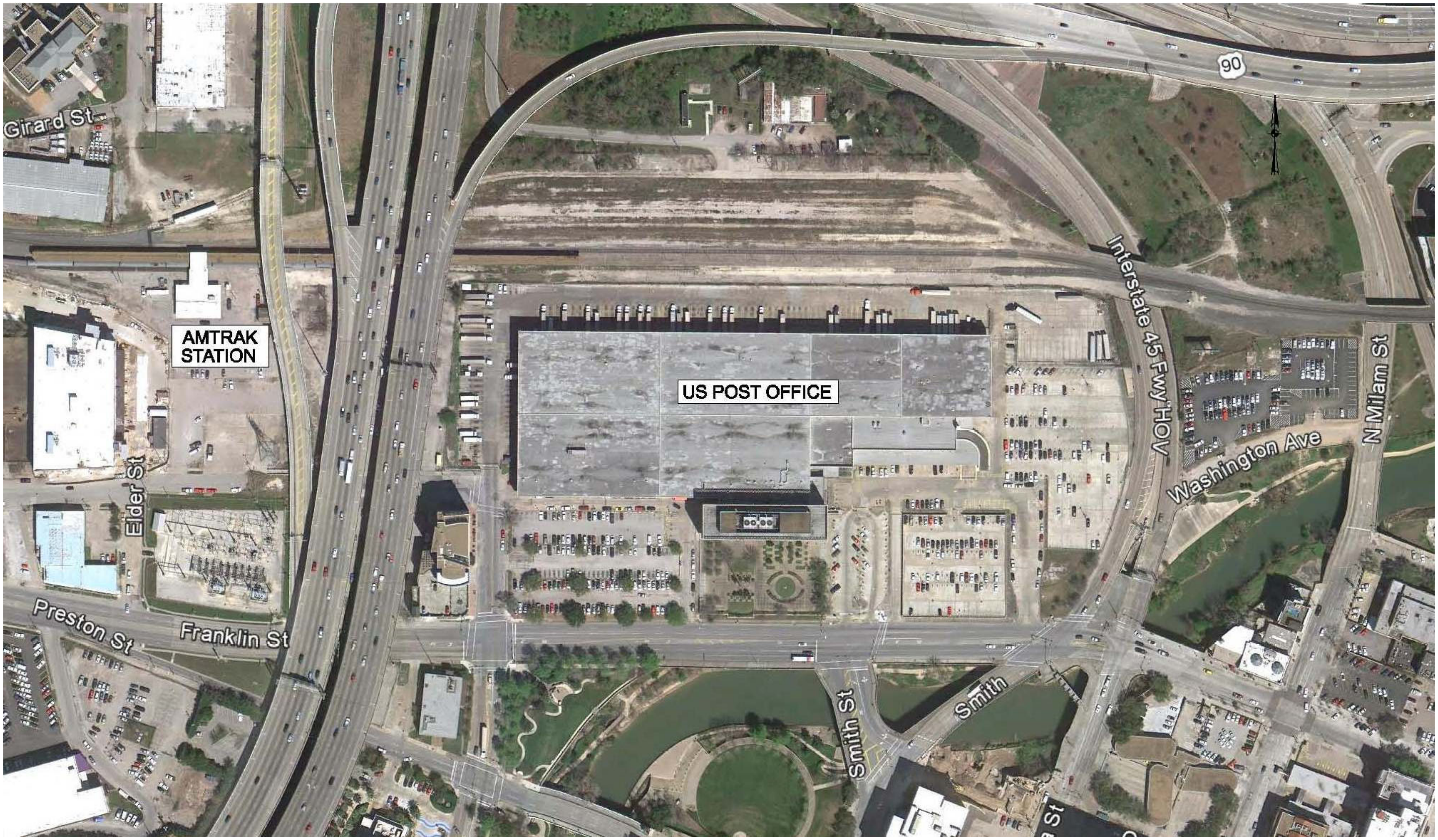


Figure 26 Development Concept for the Post Office Site as a Large Intermodal Facility Serving the High Speed Rail Terminal, Commuter Rail Station and Bus Operations Center (Page 1 of 2)

Source: TxDOT and Kimley-Horn and Associates, Inc

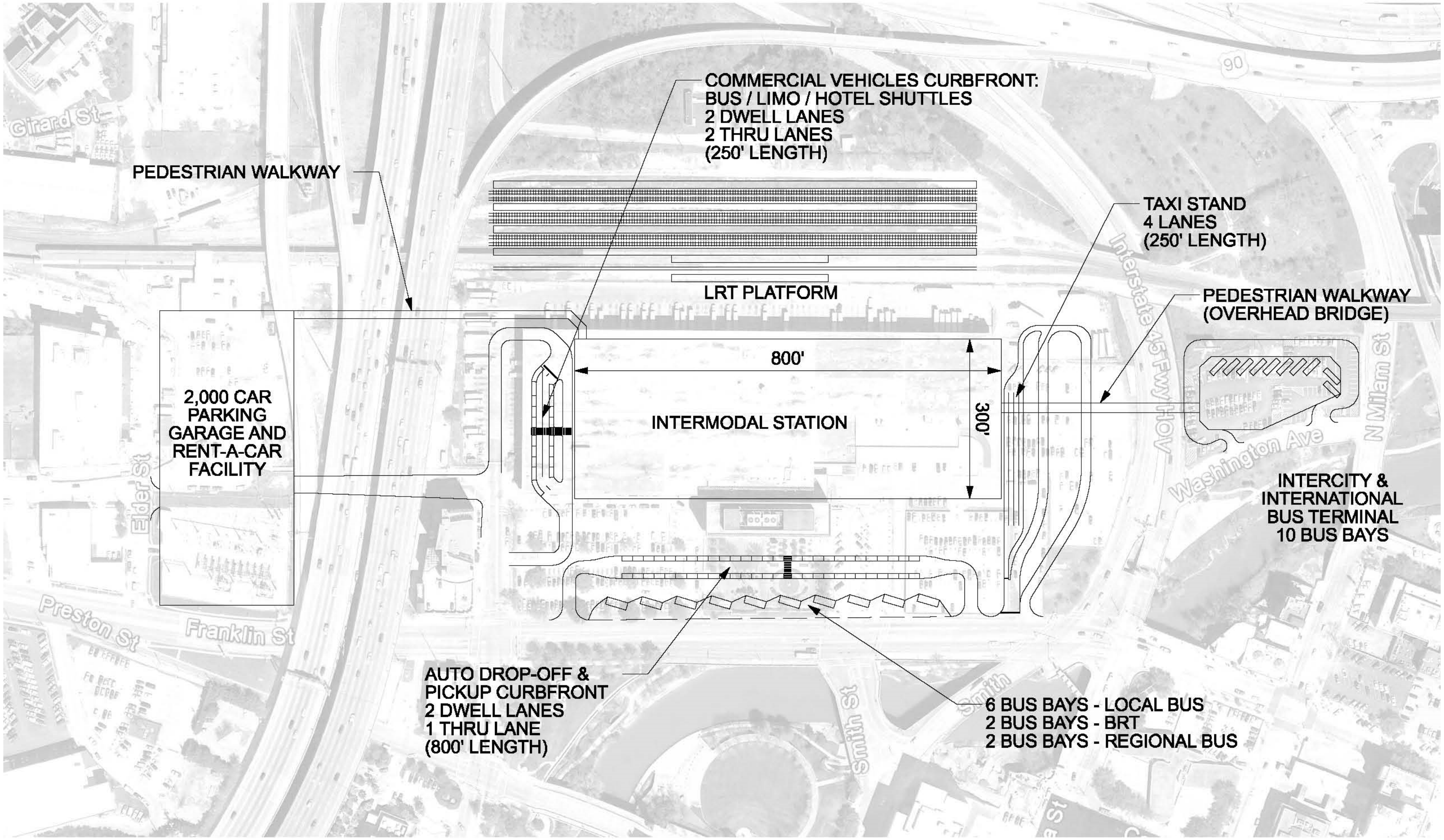


Figure 26 Development Concept for the Post Office Site as a Large Intermodal Facility Serving the High Speed Rail Terminal, Commuter Rail Station and Bus Operations Center (Page 2 of 2)

Source: TxDOT and Kimley-Horn and Associates, Inc

The ***Wheeler/Blodgett Transit Center*** site mentioned above is in direct proximity to the IH-69 freeway corridor in which HOV lanes already exist to the west of Downtown. Expansion of the transit center is currently in design to add a second platform for the LRT System and to increase the number of bus bays in coordination with TxDOT's pending construction that will depress IH-69 through that location. As shown in **Figure 20** and **Table 3** above, the potential transit ridership that would board/alight at this location is very high, based on an assumption that HCT services are deployed with sufficient capacity along the Westpark/Richmond and IH-69 corridor. The transfers to both the METRO Red Line along Main Street and to an Urban Core Transitway System would make this intermodal facility very strategic in its importance.

Placement of the ***Texas Central High Speed Rail Terminal*** at the site of Northwest Mall adjacent to the US 290/IH-610 interchange has been identified by Texas Central Partners as the planned location for the Houston terminus of the Houston to Dallas high speed rail system. Recently, Texas Central has also announced their collaboration with Amtrak to provide service to this HSR terminal by Amtrak's intercity long distance trains. This collaboration will make the HSR Terminal an excellent location for a strategic intermodal facility with connections to other transit modes. When combined with METRO's nearby ***Northwest Transit Center*** (currently the planned northern terminus of the Uptown BRT Line), this area at the northwest corner of 610 Loop becomes very important to assess for one or more strategic intermodal facilities.

Finally the ***Bellaire/Uptown Transit Center*** located adjacent to the IH-69/IH-610 interchange will serve as the southern terminus of the Uptown BRT Line, and it will have direct connectors from the IH-69 HOV lanes into the transit center. This combination of transit services qualifies it to also be considered as a strategic intermodal facility.

<u>**Intermodal Station Configuration**</u> – The configuration of complex intermodal stations typically requires some separation of modes between different levels of the facility – especially when fixed guideway rail systems are being interconnected with roadway vehicles. **Figure 27** shows this type of multi-level intermodal station in Downtown Miami at the Government Center Station serving the subregional corridor Metrorail system on the third level, the Downtown District Metromover grade-separated transit circulator system on the second level, and local service buses and pedestrian access at ground level.

Source: Google Maps

Figure 27 Government Center Station is a Major Intermodal Facility Providing FM/LM Connectivity Between Miami Metrorail Regional System and the Downtown Metromover Circulation System

Within this type of intermodal facility, the pedestrian movements and spatial provisions must be adequately designed for ticketing and waiting areas, and for internal corridors and external pedestrian pathways. For boarding platforms the spatial area must be sufficient to accommodate the combined surge flows of alighting passengers and boarding passengers, especially with the new operational concepts of mobility-on-demand in which passengers must wait at the boarding location/platform until a vehicle arrives that is bound for their destination.

In the future the importance of AV Transit technologies will reshape how HCT intermodal stations operate and how they are configured, especially with design configurations that must accommodate both large AV Buses and AV Microtransit vehicles. This reconfiguration should begin to be included in Houston's planning studies of intermodal facility ROW, access roadways and passenger boarding platforms.

HCT intermodal stations should be able to evolve into a design for AV Transit similar to what METRO has been building at their largest transit centers and/or park and ride lots for many years. With the advent of fully automated AV Buses, this station concept using individual vehicle berths will still be relevant, even for buses arriving in platoons (which can be viewed as "virtually coupled" vehicle entrainment).

Figure 28 (taken from the TRB study performed recently by TSU, refer to Footnote 5.) illustrates this concept of off-line stations which can allow platooning vehicles arriving as virtually "coupled" trains to separate for the purpose of entering separate vehicle berths. The configuration of separate vehicle berths also accommodates multiple vehicles of a variety of sizes, allowing both full size automated buses and Microtransit vehicles to serve passengers from the same berths.

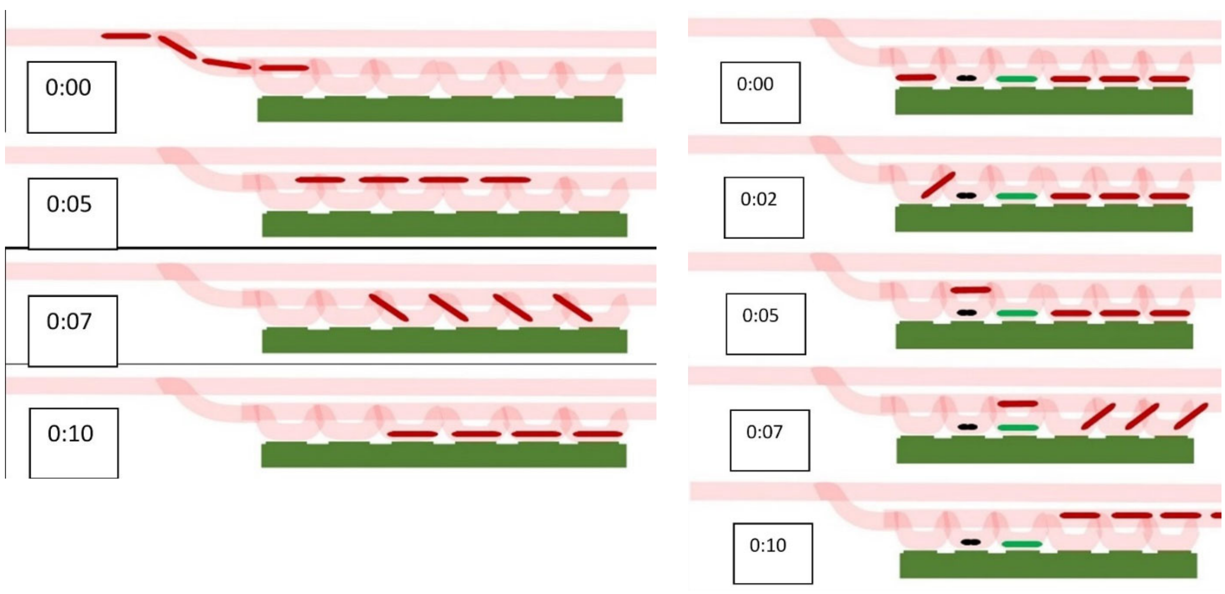


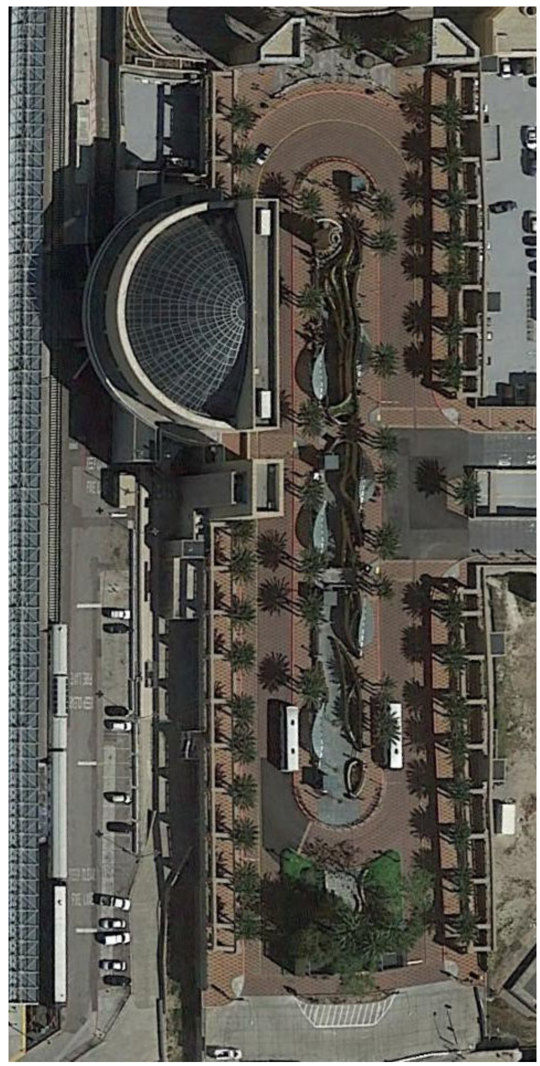
Figure 28. Virtual Coupling and Uncoupling of Vehicles Allows Individual Vehicle Berthing in Stations and Dynamic Reconfiguration of Bus Platoons at Each Station

The configuration of off-line stations with individual vehicle berths will not only allow very flexible operations that include different size AV Transit vehicles, it will also allow dynamic reconfiguration of bus platoons between common station stops. **Figure 28** also illustrates this dynamic reconfiguration of operations that become possible with the station configuration being described. These configurations can be applied to regular transit stations stops along a corridor, as well as in major intermodal stations where people are transferring between different transit modes.

Two major transit hubs which are examples of this type of configuration are in El Paso adjacent to the Downtown border crossing into Mexico, and the bus terminal at Los Angeles Union Passenger Terminal – one of the larges intermodal rail and bus terminals in the United States. See **Figure 29** for aerial photographs of these example transit centers. Note that both of these transit hubs have substantial amenities for passengers, including in the case of some major transit centers in El Paso where air conditioned facilities are provided for passengers to wait until the arrival of their bus is announced on video displays.

Refer also to **Appendix D** for a more comprehensive discussion of the configuration of stations that will best serve the future AV Transit vehicles and operating strategies which will be common in the future.

El Paso Sun Metro
Downtown Transit Center



Los Angeles
Union Station

Figure 29. Off-Line Bus Station Configuration with Individual Vehicle Berths

Source: Google Earth – El Paso, Texas; Los Angeles, CA

3.4 Rail Systems in Strategic Corridors for Sustainability, Resiliency and Reliability

Houston must begin to think of its overall transportation system in terms of both the sustainability of operations as massive growth occurs, as well as reliability and resiliency during times of extreme weather events or other catastrophic events that may require an evacuation of portions of the region. As discussed throughout this paper, building in high capacity transit elements that will support long term, sustainable growth will be critically important as our roadway systems become heavily congested. AV Roadway Vehicle transit operations will also be susceptible to the impacts of roadway operational failure in locations where transitway lanes connect to the regional roadway system. Transportation planning must also be undertaken to address other high capacity modes which are separate from the roadway system.

Further, we know that our freeway/ highway system has shown during past hurricane evacuation events that it cannot adequately accommodate the massive traffic flows. Equally concerning is the current survey data beginning to indicate that future societal trends will result in many urban residents not even owning an automobile. These urban residents will primarily rely on the public transit system and ride-hailing car services (now being called transportation network companies – TNCs) and will therefore need some means of evacuating the region when such orders are given. In those situations some type of very high capacity transportation system that is separate from the roadway system will be needed to safely evacuate these most vulnerable portions of the population.

The benefit of elevated transitways for Houston can be effectively emphasized in light of these evacuation concerns when the dramatic impact of Hurricane Sandy in 2012 on the New York City metropolitan area is considered, particularly with regard to the extensive flooding of transit subway tunnels and the inundation of surface transit lines. Alignments and ROW along an aerial transitway – particularly within the Urban Core – will provide the most reliable operations before and after a major Gulf Coast weather events such as the extensive flooding of Hurricane Harvey and the roadway grid-lock cause by the evacuation in 2005 when category 5 Hurricane Rita was originally forecast to hit Houston.

Passenger Rail Systems placed in a few strategic corridors would, for the reasons stated above, provide the region a way to achieve a level of transportation system reliability and resiliency when faced with even the most extreme conditions of regional evacuations. **Figure 30** illustrates this concept of including a high capacity passenger rail line(s) with the overall multimodal transportation system plan.

In some corridors where moving very large numbers of people is considered of critical importance, there could be a practical HCT solution of deploying advanced metro-rail technology that is operated with 21st Century capabilities of fully automated controls. These types of automated "heavy rail" systems can be designed to carry the maximum possible number of people. In fact, fully automated passenger rail systems capable of carrying 30,000 to 40,000 passengers per hour per direction or more are now in operation all over the world. Over the long term, the Houston Region will need this level of carrying capacity in a few strategic corridors. **Figure 31** shows two of the automated metro-rail systems from the cities of Dubai and Vancouver that have been recently studied by H-GAC (refer also to **Appendix A**).

Some types of rail technologies should also be included which can provide high capacity service extending to towns and cities away from the Gulf Coast. This is relevant to consider as part of this HCT paper, since these same "Intercity" passenger rail technologies can also provide regional/express service during the normal weekday peak periods – a service type that is also commonly called "commuter rail".

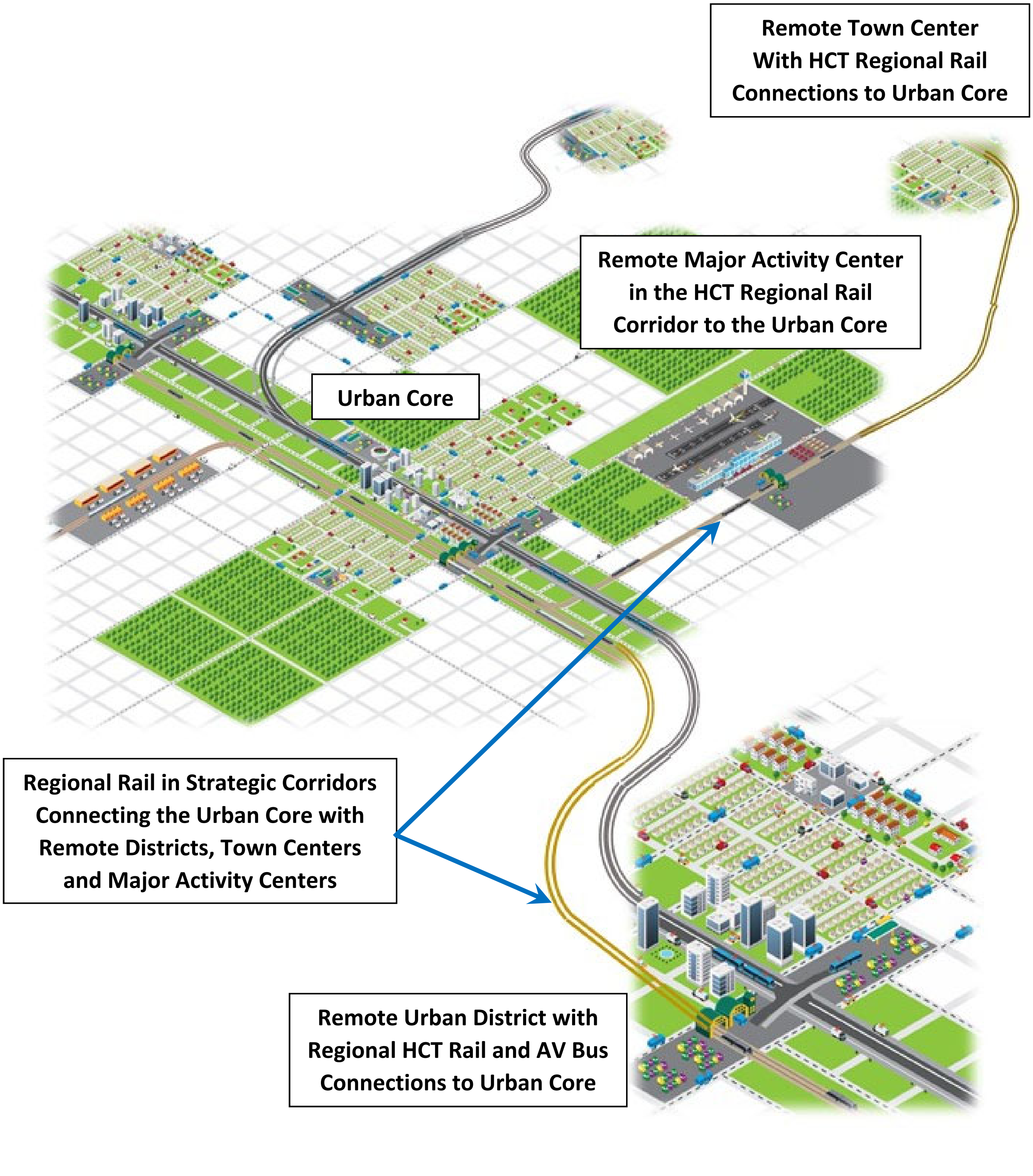


Figure 30 Strategically Located Passenger Rail Lines Add Sustainability and Resiliency Characteristics to a Multimodal Transit System

Source: Houston-Galveston Area Council

Source: Dubai RTA Metro; http://www.dubaimetro.eu/public-transport/

Source: Mobile Syrup Online Magazine, https://mobilesyrup.com/2018/05/23/freedom-mobile-customers-wireless-access-skytrain-dunsmuir-tunnel/

Figure 31 Subregional Corridor Service Concept Examples of Automated Transit System (ATS) are taken from Dubai UAE, RTA Metro and Vancouver Skytrain

For example, this blend of intercity and regional commuter rail services is provided by Amtrak every day within the Northeast Corridor, especially into and out of New York City. Similarly, Amtrak provides these same type of services along the West Coast. **Figure 32** shows a graphic taken from the Amtrak website (see figure reference source) with the red lines indicating the train travel routes on which Amtrak trains operate every day in Southern California serving the stations shown in blue. Amtrak provides a service very similar to and supplemental to Metrolink – the regional commuter rail service operator.

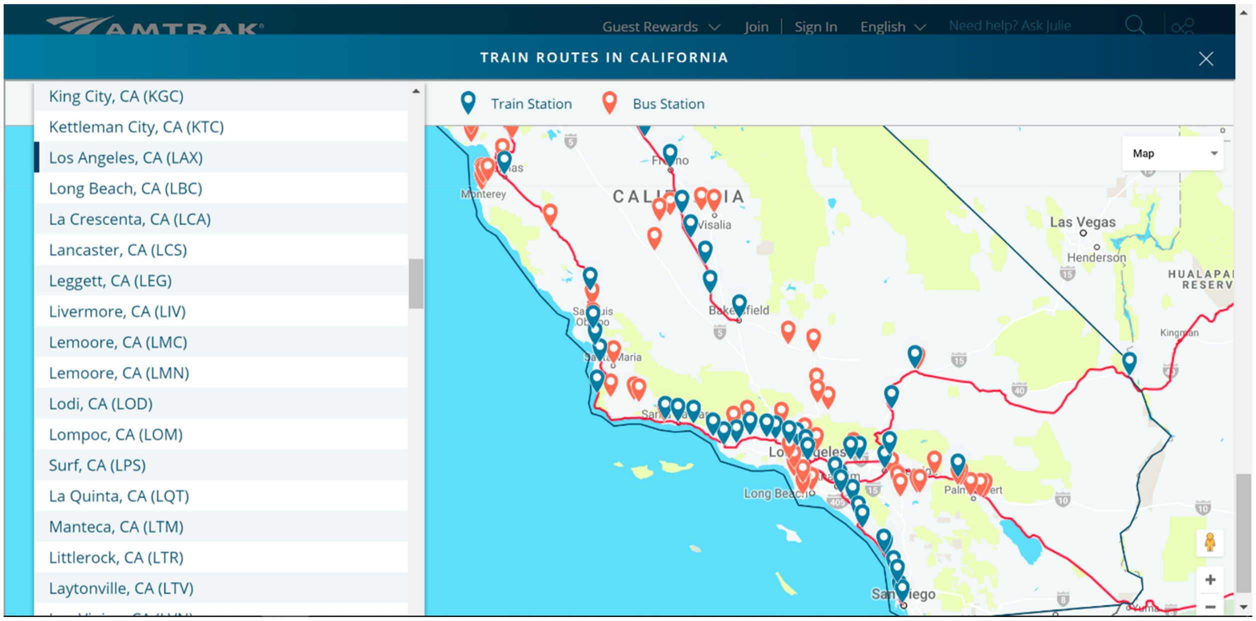


Figure 32 Amtrak Intercity and Regional Train Service throughout the Los Angeles Region
Source: Amtrak https://www.amtrak.com/california-train-routes

Through these operating routes that cover much of the LA region, Amtrak also provides Regional Express Services which bring commuters into and out of LA "Union Station" every weekday. This LA intermodal station – officially called Los Angeles Union Passenger Terminal – is also one of the main long distance terminals for Amtrak. About 100,000 commuters connect everyday between Amtrak and Metrolink trains and LA Metro's buses and BRT lines, heavy rail subway system, and light rail transit lines that run throughout the region. **Figure 33** shows an Amtrak train running on the "Surfliner" route between LA Union Station and San Diego.

For Houston, a "system approach" to a regional high capacity, multimodal transit system should include strategic corridors where very high capacity rail service is provided – similar to the many corridors where Amtrak intercity/ regional trains operate in LA.

Figure 33 Amtrak Service Through LA Union Station
Source: http://www.trainweb.org/amtrakpix/travelogues/101515A/102615A.html

Where railroad right-of-way and track infrastructure can accommodate passenger service, there should continue to be an assessment of selected corridors where classical commuter/ inter-city passenger rail services could be deployed. This type of passenger rail operations along a combined freight and passenger rail network can be accomplished safely using modern positive train control (PTC) technology.

However in order to operate passenger trains on the railroad network, there will need to be important increases to the freight railroad network capacity, in addition to creating the added safety of an advanced railroad PTC system. Having sufficient capacity for freight rail operations will determine whether in the future there is also capacity to allow passenger trains to operate on selected corridors within the railroad network. **Appendix E** addresses an approach to increasing the railroad network capacity. This approach has been proposed as an extension of past studies which assessed where in the railroad network commuter rail trains could most beneficially operate during the hours of daily work commuting. **Figure 34** illustrates the creation of a high capacity, completely grade-separated freight rail system (roadways pass above or below the tracks) and a representation of the possible passenger rail lines that would be able to operate on the railroad network with the added network capacity.

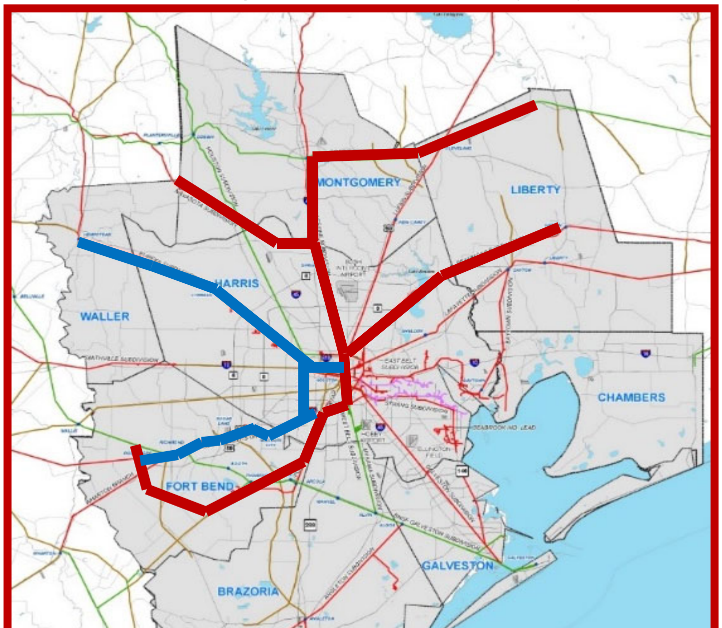


Figure 34 Proposed Concept for Creation of a High Capacity Freight Corridor System (Red) With Passenger Rail Service in Example Corridors (Blue)

Also discussed in **Appendix E** is the case for building this high capacity freight railroad system, with an example of how it could actually save the region significant cost when compared to the other options for provision of passenger rail service. Several studies of the Fort Bend Railroad Bypass completed under the auspices of the Gulf Coast Rail District have shown that under a benefit-cost analysis, approximately $1 billion in benefits is achieved by building the Bypass for freight rail operations. This benefit is derived from the cost savings of diverting freight trains through the Bypass with all roadways completely grade-separated, thereby allowing passenger rail service to run on the existing UP Glidden Subdivision railroad line along the US 90A corridor. The comparison of costs was based on the alternative of building new passenger rail track on a separate horizontal and vertical alignment from freight rail, which would require that the passenger tracks be grade separated for much of the length – primarily through the Sugar Land area.

High Capacity Rail Technologies Operating in Selected Corridors which could accommodate either HCT Subregional Corridor service or Regional/Express services are discussed below. No specific alignment is identified in the conceptual discussion that follows, although the benefits to achieving a sustainable, reliable and resilient transportation system are discussed in broad terms.

West Into Growth Areas – The largest portion of the new residents that will move into Houston over the next 30 years will populate the suburban and exurban band that is to the west of Houston. This huge growth area can best be served in a sustainable way if at least one very high capacity rail line is built into this part of the region, connecting it to the highest density of employment centers in the Urban Core. As can be seen from the transit demand potential in **Figure 15** above, there will also need to be high capacity transit lines running north and south along major travel corridors like the Grand Parkway, Highway 6, and Gessner/Beltway 8 – all of which also interconnect this West HCT rail line with other employment centers along these corridors.

South to Coastal Communities – Equally important would be the creation of a very-high capacity rail line to the south end of the region. This area of coastal communities is both a high growth area that is important to support with sustainable transit services. But even more important is that these communities are in parts of the region for which it is essential to provide emergency passenger transport capabilities when severe weather events require a mass evacuation to be implemented. Furthermore, connecting a South HCT rail line with other lines traveling north and west from an intermodal station in the center of the region would provide a sustainable passenger transport capability that we will needed when our region has doubled in size by 2050.

North to Safety from Hurricanes – The travel corridors to the north will be strategically important to address when sustainable growth is considered, and especially when transportation system reliability and resiliency must be ensured during major evacuation events. In many aspects, the most certain path to a safer location when a major hurricane is approaching would be to the north. Amtrak passenger rail service such as discussed above which provides both intercity and Regional/Express HCT Service may be a good North HCT rail option. The high speed rail system connecting Houston to Dallas will also provide a portion of this strategic transport under emergency conditions, as long as the HSR terminal location is well connected to HCT service from other parts of the region.

The Challenge of Implementing Rail Systems comes with multiple facets of program complexity, all of which must be addressed on a scale that could be beyond a single public agency or a single private company's resources and capabilities. The aspects of capital and operating costs, funding/financing, implementation complexity and environmental/societal impacts – especially when the rail lines extend from the edge of the region into the Urban Core – are key elements of the challenges which may call for a public-private partnership (PPP) approach. PPPs which address the large costs and complexity of rail systems are important to consider for implementing major rail projects such as those described in this opinion paper – especially when changes to the privately owned freight rail network are involved.

Further, the scale of a major rail project requires the building of a unified political will in order to accomplish these key components of the multimodal high capacity transit system. Houston has suffered in the past from some elements of the local political structure opposing large scale transit projects. In order to meet the challenges of mobility described above, a unified political will is critically important to establish and maintain.

The one parameter that shapes most of the other aspects of a major transit project is the initial capital cost to build a significant rail line. Costs ranging from $50M to $200M per mile are typical, depending on the vertical and horizontal alignments and the associated combinations of segments with at-grade ROW and segments with aerial structures, as well as the placement and configuration of stations. A 40 mile passenger rail line would typically cost on the order of $2B to $4B, depending on the corridor's physical constraints, available ROW and the extent to which the alignment must compensate for leaving other infrastructure and/or communities undisturbed.

Example of the Fort Bend Bypass Project – **Appendix E** describes the Fort Bend Bypass project which would allow passenger trains to operate along the existing Glidden Subdivision adjacent to U.S. 90A highway by building a dedicated freight rail corridor as a bypass through the southern side of Fort Bend County. But for the dedicated freight rail bypass corridor to work well, the terminal railroad network in the center of the region where the Bypass would connect must have existing capacity constraints mitigated either before the Bypass is built or concurrently with the Bypass project construction.

This well-studied project is an example of how public-private partnerships related to passenger rail systems will be needed to not only create the passenger rail infrastructure, but as importantly to also address capacity constraints of the existing freight rail system inside the Urban Core. Sufficient freight rail improvements have to be made to the privately owned railroad prior to the creation of the proposed passenger rail lines operating on the Glidden Subdivision or on new track within the UP owned right-of-way. But with the proper mitigation of the freight system's existing capacity constraints, passenger service of the type described in this opinion paper can then begin to be operated through selected corridors within the railroad network.

Example of the Navasota Subdivision – A similar example considered in the past would be to upgrade freight rail capacity on the north side of the region by constructing suitable capacity improvements along the Navasota Subdivision such that operations of passenger trains can begin in the northwest sector of the region. The Navasota Subdivision spans east and west between the UP Eureka Subdivision at Navasota to the Palestine Subdivision running north from downtown Houston. If the Navasota Sub was upgraded to a form similar to that of the proposed Fort Bend Bypass, then it would be possible to operate passenger rail service along the Eureka Subdivision adjacent to U.S 290.

These two passenger rail lines, one running northwest through the U.S. 290 corridor and the other line running southwest through the U.S. 90A corridor, can be seen as blue lines in **Figure 34** above.

In summary, it is essential for public investments to be made for the purpose of mitigating capacity constraints of the privately owned railroad network if passenger rail service on the railroad network is to occur. For this to be accomplished, the overall goal and purpose of the public investment, along with the nature of the investments must be understood and embraced by our regional decision makers. Further, financial plans must be developed and governmental commitments in partnership with the private Class One Railroads must be made first, before the process of passenger rail infrastructure design, construction and operations can be fully engaged.

4.0 A Case Study of the Westpark/Richmond Corridor

The planning process by which high capacity transit is evaluated for a given corridor will determine what are the Service Concept(s) and even the technology(ies) to be deployed. For purposes of this paper, one example corridor will be discussed with respect to this Service Concept(s) and the comparative technology assessment. As part of this assessment, the implications of the line's operational impacts, ROW requirements and potential cost will be briefly considered. In addition, an example of an evaluation methodology of corridor and technology characteristics is included below. This type of evaluation is typically applied during the alternatives analysis process.

The corridor chosen for this exercise is the Westpark/Richmond Corridor. This exercise is not intended to be a recommendation, but rather a way to view the implications of various high capacity technologies that could be deployed in this corridor. The Westpark/Richmond Corridor has a unique status within the region in light of the following points:

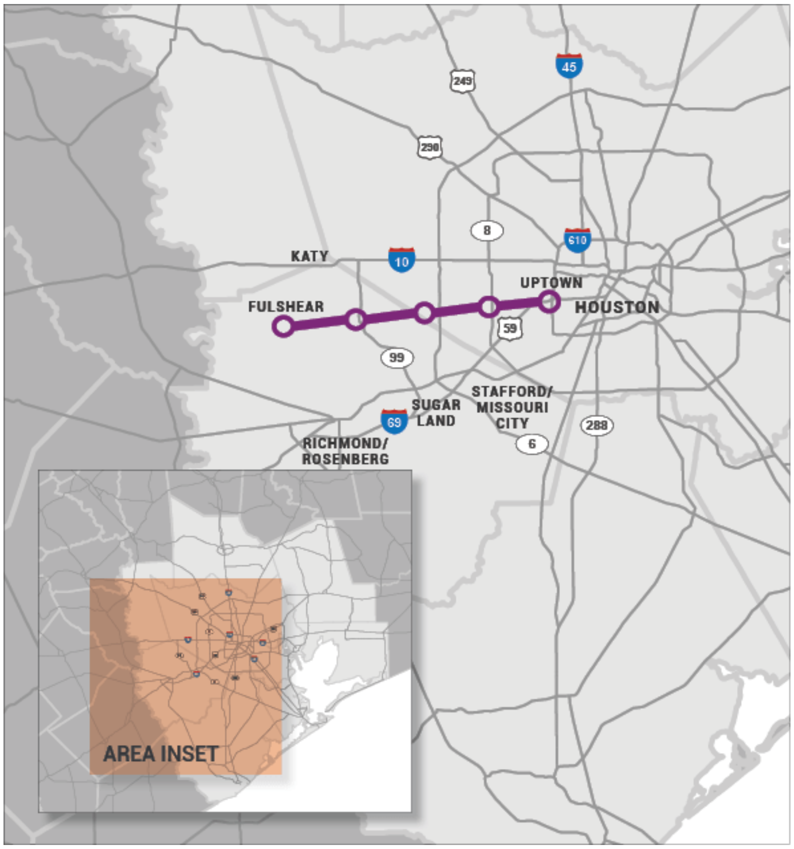
1. No current high capacity transit operating within the corridor (other than a parallel segment of IH-69 with an HOV lane).
2. Highest demand corridor in total daily boardings resulting from the H-GAC HCT ridership forecast modeling, as shown in **Figure 15B** and **Table 2.** [15]
3. Passes in proximity to 6 urban districts and major activity centers (Westchase/Energy Corridor, Uptown, Greenway Plaza, Texas Medical Center, Downtown and the University District).
4. Connections to 3 major Intermodal Stations (Gessner/BW8, Bellaire/Uptown and Wheeler/Blodgett), and 3 additional METRO Transit Centers and park and ride facilities (Mission Bend, Westchase and Hillcroft).
5. Passes directly adjacent to the Gulfton area which has the highest density of residential population in the region, as well as a large population having a high transit dependency.
6. Parallel to one of the most capacity constrained segments in the roadway system – IH-69 between the Spur 527 connector to Downtown and the 288 interchange.
7. Publically controlled right-of-way (ROW) along the former Bellaire Subdivision railroad line, which has a ROW width of approximately 50' for most of the roughly 22 mile length between Kirby Drive and 99 Grand Parkway and with a constrained width of 26' continuing west of Grand Parkway.
8. One additional major point of connection is also possible if the line would be extended to either the Eastwood Transit Center (as METRO is considering for the Richmond Line) or to the conceptual Congress Yard Intermodal Station on the east side of Downtown, as discussed above.

Figure 35 is a conceptual route map of a portion of the Westpark/Richmond corridor which addressed the possible commuter rail options west of IH-610 West Loop. This figure shows one of the multiple corridors analyzed in the GCRD Regional Commuter Rail Feasibility Study that was referenced in the previous section (see footnote 14.). The following discussion compares the deployment pluses and minuses of alternative technologies: commuter rail, light rail, AV Bus/BRT and automated metro-rail (also referred to as an automated transit system technology – ATS).

[15] For the 2045 HCT Vision Plan ridership analysis, H-GAC assumed that the line would extend through the CBD north to connect to the Lockwood Transit Center. The discussion in this Opinion Paper is limited to the corridor from the western edge of the region to Downtown and does not include this north extension.

4.1 ROW, Infrastructure and Cost

The original 100' ROW was purchased by METRO from SPRR in 1992 between Houston and Fulshear, and about half of the ROW width was sold to the Harris County Toll Road Authority (HCTRA) in order to accommodate the construction of the Westpark Tollway. This reduced the ROW width to a nominal 50' width between IH-610 and SH 99 Grand Parkway. West of Grand Parkway the ROW has been reduced to a 26' width to accommodate the Fort Bend County Tollway Authority's west extension of the Tollway. However, inside Loop 610 the original ROW remains with a width of 100' for a short distance inside Loop 610, then approximately 50' to a point east of Kirby Drive, with high-tension electrical power transmission lines straddling the ROW.



The 27 mile commuter rail route alignment shown in the graphic was assumed in the Gulf Coast Rail District's Regional Commuter Rail Feasibility Study (ref. footnote 14) for purposes of assessing the feasibility of building the line within the existing ROW as it was still preserved for high capacity transit at the time of the study in 2015.

Figure 35 Conceptual Route Map for the Westpark Corridor

Studies performed in 2015 for the Gulf Coast Rail District specifically considered how a conventional commuter rail line could be installed within the METRO controlled ROW. The conclusion of the study was that within a number of segments (particularly west of Grand Parkway) the ROW was so narrow that a double-track installation would require an elevated structure – resulting in a relatively high cost to deploy classical commuter rail service in this corridor. **Figure 36** shows the studies for the passage of alignment through the Westpark Tollway interchange with Beltway 8/Sam Houston Tollway where a portion of the alignment was aerial and a portion transitioned to grade within the existing ROW.

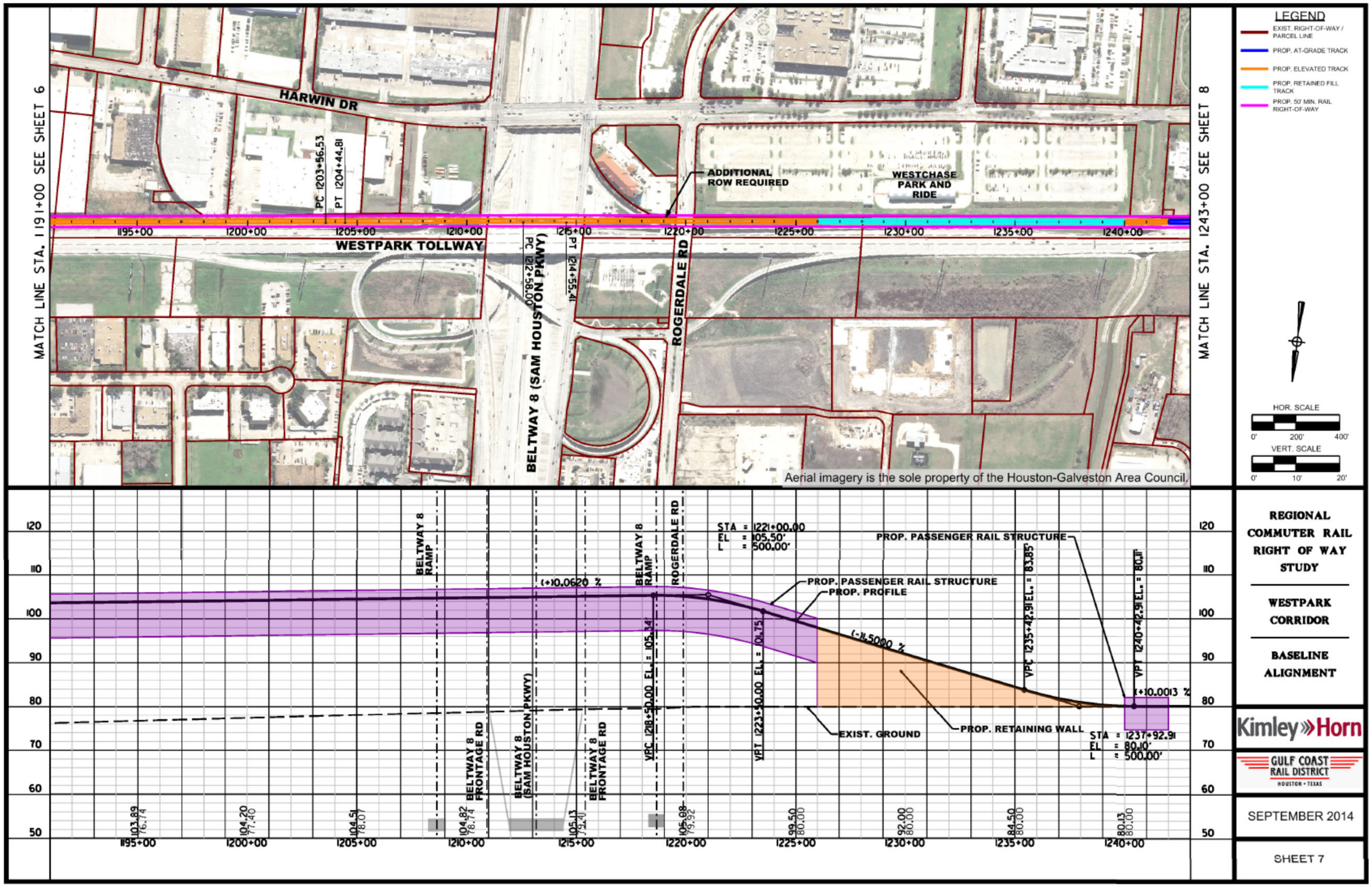


Figure 36 2015 GCRD Study of Commuter Rail in Westpark Tollway Corridor at Beltway 8/Sam Houston Tollway interchange

Source: Gulf Coast Rail District's Regional Commuter Rail Feasibility Study (ref. footnote 14)

For the baseline alternative that placed the 27 mile route alignment at grade in almost all locations except in the constrained ROW throughout the roughly 8 mile length where an aerial structure would be required between SH99 Grand Parkway and Fulshear, the capital cost was estimated to be about $1.5 billion[16] (2014 dollars), for an average of $55 million per mile over its total length. This baseline included aerial sections passing over the existing Westpark Tollway entry and exit ramps between the Harris County Line and Grand Parkway.

For the roughly one mile long segment immediately west of IH-610 where the line was assumed to terminate at the Bellaire/Uptown Transit Center, an aerial alignment option was estimated to add about $65 million to the total cost, and a below-grade alignment in this location was estimated to add $125 million to the total cost.

This capital cost development produced an order-of-magnitude average cost ranging from roughly $20 to $50 million per mile for a double track configuration and an alignment mostly at-grade (the cost variance was based on the local conditions throughout the route length, such as locations where bridges and embankments would be required). For the western end of the alignment where a double-tracked aerial structures were continuous, the average coast was roughly $75 million per mile (not including vehicles, stations and other support facilities).

A more recent study of the corridor also performed under the auspices of the GCRD and Harris County, working with HCTRA and Houston METRO, determined that a BRT line would be less costly deployment within the ROW limitations.

The choices for a vertical alignment placed at-grade versus on an aerial structure have a direct impact on the capital costs of a high capacity transit line, no matter what technology is deployed. A general rule of thumb is that an aerial alignment costs twice as much as an at-grade alignment, and a subsurface alignment costs four times as much as an at-grade alignment. In addition, the cost of station facilities is also significantly higher when placed at the height of the aerial alignment or especially when located below grade. One advantage of aerial or underground stations, however, is that a station configuration with center platforms allows pedestrian access to be efficiently provided to the one platform for access to trains in either direction without requiring pedestrians to cross active transitways (as is the case for many LRT stations in Houston).

Intermodal stations at BW8/Gessner, Bellaire/Uptown Transit Center, and Wheeler/Blodgett would certainly require a fairly large footprint to handle the number of passengers passing through each day, as indicated in **Table 3** and **Figure 20**. In addition, the multiple modes that would be served at these intermodal stations will probably require a multi-level station facility with vertical circulation systems between the boarding levels for the different modes/technologies.

One of the cost savings of commuter rail, light rail and BRT when compared to fully automated metro-rail /ATS is because it is possible with the first technologies to cross streets and highways with a signalized and/or gated crossing which activates as the transit train/vehicles approach the surface roadway. This signal "preemption" is currently how most of the Houston METRO LRT system operates as the lines pass

[16] Civil costs and PTC signaling included, but without new ROW purchase, utilities relocation, vehicles, stations or support facility costs.

through the surface street operating environment. The impacts of this mode of operation on the roadway traffic operations along the transit alignment are discussed in the next section.

Another cost advantage for rubber-tired AV Bus/BRT technology applications is the option to "single-track" through a narrow ROW section – a configuration much more easily created and operated with rubber-tired AV buses compared to tracked vehicle systems.

In all cases of the technology alternatives being discussed, there is now a precedent that a signaling system with a high level of automation will be required to operate safely – even for commuter rail and BRT system technologies when operated as high capacity transit. This signaling system infrastructure, and the related communications systems necessary to monitor the operations and to protect the passengers riding the system, will be similar for all of the technology options.

All of the technologies would be essentially equal in providing intermodal connections at the key station locations along the corridor. However, the length of the commuter rail and the metro-rail trains could become substantially greater than the LRT trains when the greater maximum capacity of these heavy rail technologies is implemented. This would require longer boarding platforms, with associated larger cost and longer walking distances of passengers to access vehicles with available space to board along the train's length. For aerial stations these costs would be substantial, and for at-grade stations the ROW requirements would be more difficult to manage within the Urban Core.

The intermodal stations for AV Bus/BRT vehicles, however, would be easily configured to allow passengers to conveniently board at dedicated vehicle berths as described above in **Section 3.3**. The more efficient and flexible station configurations possible with non-tracked systems would therefore make the intermodal transfers more convenient for the AV Bus/BRT technology compared to the other rail technologies that have vehicles mechanically coupled together into a train. The author believes that this also adds beneficial cost aspects for AV Bus intermodal stations for which the configuration could be adjusted to fit available ROW, as has occurred with some of METRO's existing park and ride facilities and transit centers.

4.2 Capacity/Operational Characteristics and Related Impacts on other Modes

Our experience in Houston with the METRO LRT system has revealed that there can be significant detrimental operational impacts on roadway traffic when transit signal priority is given to the transit line – particularly when full signal preemption is allowed. Along the Westpark and the Richmond corridor, there are many north/south high traffic volume roadways crossing the alignment throughout its length. With the characteristic placement at-grade, some of the HCT technologies would have a similar impact on roadway traffic operations as exists with the METRO LRT when the activation of signal priority/pre-emption is combined with a frequent passage of the HCT vehicles/trains. These traffic impacts are discussed below for each technology alternative.

Commuter Rail – For purposes of this discussion a benchmark of HCT line capacity will be considered to be that of 8-car bi-level commuter rail trains operating on 10 minutes headways, since commuter rail is a HCT technology that has already been evaluated for the Westpark Corridor in past studies. Commuter rail is typically applied for service over fairly long distances in which the trip duration is 30 minutes or longer for most passengers, therefore the "seated" capacity of 1,000 passengers aboard an 8 car train[17] will be used for the benchmark.

The line capacity benchmark is established from a typical frequency of trains on a "high-capacity" route which operates with 10 minute headways in a single direction. This establishes the reference carrying-capacity of 6,000 passengers per hour per direction. A commuter rail train passing every 10 minutes with about a 30 second duration of crossing gate-arm activation is considered to have a moderate-to-high impact on traffic operations when an alignment with at-grade crossings is assumed.

This 10 minute headway is a practical minimum for a typical commuter rail line. When combined with a practical standing passenger load of an additional 50 passengers per vehicle (185 seated and standing passengers per vehicle) and 10-car trains, the practical capacity of a commuter rail line would be 11,100 passengers per hour per direction (pphpd). This frequency of train operations would be one at which grade separation of the line throughout much of its length would become more justifiable from a benefit/cost analysis consideration.

Regarding the type of service provided, classical commuter rail service is almost always Regional Express Service because the trains typically operate on the railroad network that also serves freight train operations. Within this "mixed-mode" operating environment, commuter rail service primarily operates during the peak commute periods and freight operations are more active during the non-peak periods. But in this case of a dedicated HCT line with no freight operations involved, it may also be possible to consider commuter rail technology for Subregional Corridor Service with bi-directional all-day operations within this special corridor.

[17] The seated capacity of a Bombardier bi-level passenger coach would typically be on average 135 passengers per 85 foot long coach, with about 540 seats in a 4-car train configured for push/pull operations. An 8 car train would carry 1,080 seated passengers.

Light Rail – In comparison, LRT technology configured for long distance service would have seating for approximately 75 seated-passengers in an articulate LRT vehicle – as METRO vehicles are typically configured for current Houston METRO operations[18]. To provide a capacity of 6,000 seated passengers per hour, there would need to be 4 minute headways between trains. The resulting impact on traffic operations would be major when the trains are operating at-grade and pre-empting signals at each roadway crossing.

For maximum capacity considerations of LRT trains operating along a dedicated track alignment completely separated from traffic over most of its length – as considered in the commuter rail discussion above – 3 minute headways is believed to be a practical minimum for a 4-car train running articulated vehicles. If it is assumed that 125 standing passengers were added to each vehicle (200 pass/veh), the 2 minute minimum headway would provide a comparable maximum capacity of 16,000 pphpd. One difference from the commuter rail example is that Light Rail Transit is usually operated to provide bi-directional all-day service.

AV Bus – AV Buses operating in 4-bus platoons carrying 50 seated passengers per bus (200 people onboard each 4-bus platoon) would require 2 minute headways to deliver the same capacity benchmark of 6,000 passengers per hour per direction. This means that the bus platoons would be pre-empting traffic signals every 2 minutes and the traffic operational impacts for an alignment with at-grade roadway crossings would be severe, with the highest impact on roadway traffic operations among all the HCT technologies which could operate at grade.

To consider a practical maximum throughput capacity for an AV Bus line if it were completely grade separated from crossing roadways, it is possible that 60 second headways could be sustained if the station facilities were properly sized and configured for multiple platoons arriving at this frequency. When a combination of seated passenger is added with an assumed capacity of 25 standing passengers per bus, the throughput capacity of the AV Bus rapid transit line would be 18,000 pphpd.

For purposes of this comparison, AV Bus technology would be operated as a line providing Subregional Corridor bi-directional all-day service. And further to the considerations of this “line-haul” service application, the creation of a completely grade-separated AV Bus transitway would also allow other AV Transit vehicles which are bypassing most stations in the corridor to operate in-between the entrained AV Bus platoons traveling on one minute headways.

Automated Metrorail/ATS – Finally, an 8-car metro-rail train would provide seating for approximately 400 people[19], and the 6,000 passengers per hour per direction benchmark would require trains operating on 4 minute headways. For fully automated operations, it is assumed that the metrorail system would be completely grade separated and there would be no impact on traffic operations.

[18] The seated capacity of the articulated suburban light rail vehicle as currently configured for Houston METRO’ Siemens vehicle is 72 passengers per vehicle, and 144 seated passengers in a two-car train (with additional provision for 8 wheelchairs). In comparison, the seated capacity of Austin Metrorail DMU vehicle (Stadler) is 96 passengers per articulated vehicle (one-vehicle train), and with an additional 12 fold down seats in the wheelchair locations.

[19] Seating configurations vary for metro-rail trains since many are designed for a high mix of standing passengers; however for purposes of comparison, technical references on modern automated trains in metro-rail applications indicate that seating can be configured for 40 to 50 people per car when fold-down seating is included.

For a maximum capacity comparison, the inclusion of standing passengers would provide an approximate vehicle capacity of about 150 passengers with 100 standing passengers in each vehicle[20]. In addition, 2 minute headways are very common with full automation of this class of train, which would provide a maximum capacity of 36,000 pphpd operating in bi-directional all-day service.

Comparison of Technologies – **Table 4** shows a summary comparison of headways required for different technologies to meet the Baseline seated passenger capacity. The table also shows a qualitative assessment of traffic impacts when the technologies operate at grade (except for the ATS rail technology which must be grade-separated) as well as a comparison of an ultimate maximum capacity for each of the four technologies when complete grade separation is assumed and standing passengers are included.

Table 4 Comparison of HCT Technology Carrying Capacity and the Associated Signal Pre-Emption implications for At-Grade Traffic Operational Impacts

Typical Characteristics	**Bi-Level Commuter Rail**	**LRT Configured for Long Distance Travel**	**AV Buses Operating in Platoons**	**Automated Metro on Aerial Guideway**
Seated Capacity of Vehicles	135	75	50	50
Multi-vehicle Consists	8	4	4	8
Headways (min.) to Meet 6,000 pphpd Benchmark	10 min. at Benchmark	3 min. at Benchmark	2 min. at Benchmark	4 min. at Benchmark
At-Grade Roadway Traffic Impacts	Moderate	High	Very High	None
Max. Throughput Capacity with Standing Pass.*	11,100 pphpd	16,000 pphpd	18,000 pphpd	36,000 pphpd

* Refer to the discussion above concerning standing passengers, minimum headways and the associated estimate of maximum throughput capacities which assume that the alignment is grade separated.

It is clear from this table that the operational impacts of commuter rail would affect arterial traffic with signal pre-emptions every 10 minutes for a single direction of travel. Realistically, pre-emptions would be more frequent with bi-directional all-day service. In comparison, the signal preemption frequency of 4-car LRT trains would impact traffic operations roughly 3x more than commuter rail, without even considering the impacts of trains traveling in the opposite direction. For AV Bus operations with 4-bus platoons, the impact is 5x greater than commuter rail. In comparison, with full grade separation of automated metro-rail technology at every roadway crossing, there would be no impact on traffic operations.

[20] ATS technology is commonly configured to provide high passenger boarding/alighting efficiency by having multiple doors on each side of each vehicle, combined with level-floor boarding from high-level platforms and walk through capabilities between vehicles.

To mitigate unacceptable operational traffic impacts of LRT trains and AV bus platoons, the alignment would need to have grade-separated crossings at all major roadways. Similarly, the traffic impacts of commuter rail trains would also be significant and grade separation at most major roadway crossings may also be appropriate – as was assumed in the GCRD study described in **Section 4.1** above.

A comparison of capital costs between the various HCT technologies can be approximated from the order-of-magnitude cost estimates for the Baseline Option case study in the GCRD study[21]. This Westpark/Richmond corridor line, as defined in the Baseline Option case with its large component of aerial structures for commuter rail, will have relatively high capital costs of $110 to $150 million per mile—varying according to the complexity of the segment. And based on the discussion of traffic operational impacts, it is also reasonable to state that the options of LRT, AV Bus/BRT would also have similar capital costs due to the extensive aerial structures also required to mitigate the very detrimental traffic impacts.

Because of the heavy impacts to traffic operations for technologies operating at grade, it becomes highly likely that the capital cost of aerial structures will be required to build suitable high capacity transit within the Westpark/Richmond Corridor, whatever technology is chosen. This assertion that grade-separation will be required if sufficient capacity is to be created to adequately service this corridor is based on the 2045 HCT Vision Plan forecast. This forecast (refer to **Table 2** above) indicates that the Westpark/Richmond HCT line would have the highest transit ridership demand in daily total boardings per mile of all corridors in the region.

Further, with this reality of high capital costs, it is the opinion of the author that the best alternative would be to build an automated metro-rail system in light of its much greater ultimate capacity. A fully automated rail transit/ATS technology could ultimately be expanded to provide over twice the ultimate capacity of BRT, LRT or commuter rail technologies.

[21] The civil costs from the Baseline Option in the commuter rail study of the Westpark portion of the corridor in 2014 dollars were based on placing the track on aerial structures to fit into the narrow ROW west of SH99, to grade-separate the entry/exit ramps along a significant portion of the tollway between SH99 and Beltway 8, and to grade-separate at some other major roadway crossings – such as in the vicinity of Beltway 8/Sam Houston Tollway. These civil costs are typically half of the total costs when all vehicles, stations and system elements are included, so the estimate of total costs per mile for commuter rail technology would range from $110 to $150 million depending on the segment.

4.4 Satisfaction of Typical Corridor Evaluation Criteria

When a HCT corridor study is undertaken, the alternatives analysis process typically develops a set of evaluation criteria by which the conceptual applications of technologies and service modes are then assessed. These criteria provide a framework for a uniform assessment of important aspects of the defined HCT corridor as part of the regional transportation system, as well as its suitability to serve the associated town centers, urban districts and major activity centers within the corridor. These criteria are not typically established as "pass" or "fail" criteria, but rather as a framework of thought to focus insight into the benefits of certain alternatives over other alternatives when evaluating technologies and service mode applications.

In this final step of the general assessment of the Westpark/Richmond corridor, a typical set of evaluation criteria has been used to discuss the comparison of this corridor to other corridors, as well as the implications for technology and Intermodal Station implementation. While the criteria may resemble criteria stemming from the work of the H-GAC High Capacity Transit Task Force, it does not reflect the Task Force's assessment in any way. The Task Force has not endorsed the assessment below.

Some aspects of the criteria give insight into whether the Westpark/Richmond Corridor should be developed as a continuous high capacity transit line along its length between Grand Parkway and the center of the Urban Core. Other aspects relate to characteristics to consider when comparing the technology options. It is noted that for purposes of the ridership analyses and travel demand forecasting of transit ridership, H-GAC has assumed that this corridor will have "all-day", two-way service. Therefore, the travel demand assumption would suggest the Service Concept is a Subregional Corridor type of service.

The following Evaluation Criteria are hypothetical, and are only representative of criteria that would be developed by H-GAC or Houston METRO in the preparations for the corridor study. A discussion of the criteria's satisfaction by a Westpark/Richmond Corridor HCT line follows each stated criteria, and where relevant comments are included on the alternative technology options.

A. High Capacity Corridor Connections with Urban Districts and Major Activity Centers

Discussion: The Westpark/Richmond Corridor may have the highest connectivity of all the major corridors being considered in this HCT study for urban districts and major activity centers. As noted above, the major activity centers, urban districts and employment centers that have proximity to the corridor include Westchase/Energy Corridor, Uptown, Greenway Plaza, Texas Medical Center, Museum District and multiple universities.

B. Connections of Corridor's HCT Service with the Region-wide Integrated Multimodal System

Discussion: The Westpark/Richmond corridor is very well suited to connect with a number of large urban centers and high density residential areas through creation of several major intermodal centers. The corridor will directly service major intermodal stations at Westchase Intermodal, Bellaire/Uptown Transit Center, and Wheeler/Blodgett Transit Center. Further, the proximity of the eastern end of the corridor at Eastwood Transit Center makes a connection to the conceptual East Downtown Rail Intermodal Station proposed in **Section 3.3** for the Congress Yard site adds an attractive expansion feature of the corridor, as well.

Each of these intermodal stations can also be served by AV Microtransit and AV Bus systems described by the Circulation and FM/LM Service Concept operating within adjacent urban districts. These connections into the region-wide multimodal transit system will be most effective when the proposed Urban Core Transitway System is created to provide a grade-separated transitway circulation network inside Loop 610 (refer to **Section 3.2**).

C. Effectiveness as an Alternative to Automobile Travel Through Congested Roadways in the Corridor

Discussion: The HCT service provides an excellent alternative for the automobile travel mode through the corridor, particularly for those traveling through the highly congested and capacity constrained Westpark Tollway segment of the corridor. This toll roadway facility cannot be substantially expanded to a level that would be adequate to carry the travel demand that is forecast for this strategic corridor. The addition of HCT is viewed by many agencies as one of the most important additions within the corridor in order to provide an alternative to this extremely congested tollway facility. However, the combination of high capacity transit in parallel to the tollway would provide sufficient capacity to serve the increasing travel demands.

In addition, IH-69 freeway corridor segment between the IH-610 West Loop and the IH-69/288 interchange is already operating at its capacity for much of the day. The new construction of the IH-69 segment immediately west of its 288 interchange will improve some traffic operational constraints, but it will not add additional lanes. Therefore this segment of the corridor (generally referred to as the "Richmond" component of the corridor in this discussion) is also facing major travel demand overloads that can only be addressed through the addition of HCT systems.

D. Service Benefits for Economically Depressed Areas with Large Minority Populations

This transit line would also pass through two large and important communities in the Alief/International District area and the Gulfton Area, both of which have high minority and economically depressed populations. Further, the Gulfton area has the highest residential population density in the region. As a result, a HCT line within the Westpark/Richmond corridor would significantly improve transit accessibility across the entire economic and demographic spectrum of our population.

E. Service to Areas of Major Population Growth

Discussion: High capacity transit passing through this corridor would connect the center of the region within the Urban Core with the high growth areas on the western edge of the region where residential development will continue to rapidly expand. The corridor connects directly to the highest employment concentration in the region located within the Urban Core.

When this corridor is also served by efficient AV Microtransit circulation and FM/LM systems at the eastern section of the line where the Wheeler/Blodgett intermodal transit center would be located (refer to **Section 2.2** above), the fairly seamless connections at Wheeler/Blodgett transit center would then allow convenient access to the Texas Medical Center and four major universities. This integration of transit modes would connect the largest trip attractors in the Urban Core with the concentration of trip productions by the new population growth on the western edge of the region.

F. Enhancement of Economic Development within the Corridor and the Region

Discussion: The traffic congestion in this corridor is currently very serious, but it will become crippling to the entire region if high capacity transit is not added within the corridor. The IH-69 portion of the Westpark/Richmond Corridor is one of the primary means of access to the CBD and the huge employment centers within the Urban Core. The economic benefits of building HCT in this corridor are therefore of critical importance to the future of the Houston region.

G. Capacity Expansion to Support Future Growth and Development

Discussion: The technology selection will be essential to assess in light of the forecasted major increases in transit ridership over the course of time. With that consideration, the early deployment should involve a capital cost investment that would ultimately provide for an eventual deployment of a very high capacity system that is capable of serving these very high ridership levels. Therefore, it is important to not deploy a technology that is less costly in the beginning, but which cannot be expanded to serve the very high ridership that will ultimately be needed as this corridor grows into its forecasted transit demand with the highest ridership of all HCT corridors in the region.

H. Sustainability and Safety Adequate for Major Weather Evacuation Events

Discussion: This corridor can serve as one of the proposed strategic rail systems operating in the West sector of the city. This high capacity transit line, when combined with other connecting HCT lines on the west side of the region, can provide a means of evacuation from the Urban Core to locations where other long distance transportation can be more efficiently provided. The ability to move large quantities of people to the western edge of the region will be of strategic importance when evacuation conditions occur.

Furthermore, the operation of a high capacity transit line within the Westpark/Richmond Corridor will remove many automobiles from some of the most congested roadways in the region, thereby allowing more effective roadway operations during major evacuations. And if automated technologies operating on grade-separated alignments are deployed, the resulting safety for those traveling on this HCT line will be far better than can be accomplished when traveling through the extreme congestion that will occur on the freeway and tollway system.

I. Reductions in Emissions and Environmental Impacts

Discussion: Deployment of an efficient high capacity transit line within this corridor, when combined with an effective AV Microtransit FM/LM circulation system, would result in a major mode shift to public transit from the automobile mode. This will make a major contribution to the reduction of emissions, especially if the HCT technology(ies) deployed uses an electric propulsion system—such as the automated metro-rail/ATS system technology. ATS, with its overall high-capacity attributes and very high levels of service, will induce increasing transit ridership far into the future. This would make this advanced technology very beneficial to emissions reductions over the long term.

Adding to this environmental benefit will be the replacement of conventional roadway vehicles that serve as circulation and FM/LM travel modes using AV Microtransit vehicles with electric propulsion.

Summary Assessment – Overall, the deployment of high capacity transit within the Westpark/Richmond corridor – when combined with the proposed FM/LM and urban district circulation systems within the Urban Core – scores extremely high when assessed according to the framework of typical Evaluation Criteria provided in this example.

4.5 Implications for Ongoing Planning and Design Efforts

This case study of the Westpark/Richmond corridor has been a useful example of the impacts, costs and benefits of implementing HCT within a major travel corridor which has extremely constrained roadway capacities. In light of the discussion above, the following points about this corridor should be considered as transportation planning in the region progresses.

1. Definition of a HCT system for operation within the Westpark/Richmond (WP/R) Corridor which has a technology application that can provide the highest capacity level possible, since the region will continue to grow long after the 2045 time frame that has shown high transit demand potential for this corridor.
2. Preservation of the HCT right-of-way existing in the corridor which is currently controlled by METRO, COH, HCTRA and FBTRA, and advancement of the planning efforts necessary to include grade separate alignments over a large part of the WP/R Corridor route.
3. Design provisions in TxDOT roadway/freeway system construction for WP/R Corridor where necessary to accommodate the HCT line's eventual construction in a configuration that accomplishes its highest capacity capabilities.
4. Design provisions for future WP/R Corridor line installation within current planning and design development of the Bellaire/Uptown Intermodal Center and the Wheeler/Blodgett Transit Center.
5. Development of north/south HCT lines which effectively connect with the WP/R line at SH-99/Grand Parkway, Highway 6 and/or Beltway 8at the associated intermodal facilities.
6. Provision of an Urban Core Transitway System that has sufficient capacity to circulate HCT ridership from the WP/R Corridor line along a grade-separated infrastructure that adequately accommodates AV Microtransit FM/LM trips circulating throughout Uptown, Greenway Plaza, TMC, Museum District Midtown and Downtown Districts.
7. Planning concept development of an East Downtown Rail Intermodal Station at the Congress Yard site with strategic connections to the ultimate WP/R Corridor line.

Finally, the significance of the H-GAC 2045 HCT Vision Plan's travel demand modeling study results cannot be overlooked with regard to the potential transit demand forecasts along the Westpark/Richmond Corridor. The fact that this corridor had the highest total transit ridership demand of any corridor of 20 miles or less in length, as well as the highest boardings per mile of all corridors in the region (refer to **Table 2**), certainly gives it a special status. It should also be noted that this ranking is not the first time that the Westpark corridor has shown this promise when high capacity transit was analyzed to serve the far west side of the region. The 2009 Regional Commuter Rail Connectivity Study also scored this corridor with the highest ridership potential, specifically having the highest home-based work trips per mile among the 16 long-distance radial corridors that were studied (refer to the 2009 report identified in footnote 13., and the associated Appendix E Commuter Rail Relative Demand Potential from this previous study report).

5.0 Conclusions on an Integrated Multimodal High Capacity Transit System

Houston is facing a major transportation crisis in the coming years as a result of our huge growth and our inability to build sufficient roadway capacity to compensate for this growth. Travel demand forecasts indicate the roadway demands will be well above the available capacity at critical points within the roadway system, resulting in massive congestion lasting for many hours of the day as we double in size over the next 30 years. Further, growing evidence indicates that the vehicle-miles traveled will actually be larger than travel demand models are able to forecast due to empty vehicle movements through the roadway system as ride-hailing services proliferate, with the resulting dispatching of fleets of autonomous vehicles around the region.

Building a multimodal transit system with efficient connections for transit users from high capacity transit (HCT) corridor systems to AV Microtransit FM/LM circulation systems will significantly enhance the viability of public transit for many Houstonians currently driving their own automobile. In so doing, this multimodal HCT system will attract very large numbers of people to use this transit option for daily travel. However, we are far behind the other largest metropolitan regions of the world with respect to preparing for an extensive high capacity transit system. This fact makes the planning of an integrated multimodal transportation system extremely important to our future quality of life and the region's continued economic development.

The HCT regional transit system will be strongest when combined with a supporting new system of AV Microtransit circulation and FM/LM systems within town centers, urban districts, and especially within the Urban Core where it can be coordinated and connected to the existing conventional local transit services. Advanced technology AV Buses/BRT deployments operating through our extensive HOV lane system will be the backbone of our future HCT system, creating an essential requirement for continued expansion of the HOV lane facilities in the median of the freeway system such that bidirectional HOV service can operate all day long. Added to this should be rail technology applications in both Subregional Corridor and Regional Express types of service for those corridors which analyses show would be beneficially served by these higher capacity technologies. Houston has developed with the largest employment centers configured in a dense cluster within the Urban Core. This means that the radial HCT lines carrying workers to and from their employment in the Urban Core must be the focal point in building the interconnected HCT network, with other HCT lines spanning between the radial corridors.

Creating such transit infrastructure which allows bi-directional, two-way travel throughout the service day will also allow Houstonians the option to use public transit, even if they live in the Urban Core and work in an employment center on the outer edge of the City. This option to "reverse commute" on the HCT as efficiently as those who "commute inbound" every morning to the Urban Core. This is an essential attribute that must be provided by the region's 21st Century multimodal transit system.

In order to create a well-connected high capacity transit system for the region, within the Urban Core a series of AV Microtransit circulation systems serving the major urban districts will be required. Then starting from these urban district circulation systems, a grade separated Urban Core Transitway System can be created which connects these urban districts with multiple large intermodal stations in strategic locations, thereby facilitating a broader circulation between the districts and major activity centers around and inside Loop 610.

Finally, the HCT system will be able to provide a one-seat ride for many transit users at the point when high capacity transit is built around AV Bus operations in many corridors through an enhanced HOV lane system with direct connections into the grade-separated Urban Core Transitway System. This attribute alone will significantly increase transit ridership throughout the region.

The many HCT lines envisioned through H-GAC's 2045 HCT Vision Plan studies could seem daunting to build when considering their scale and their scope. But to reduce the vision to a lower level will encumber the region with insurmountable transportation challenges for future generations of Houstonians. Completion of the HCT Vision Plan is essential in order to inform our policy leadership of the needs and benefits of creating mobility and access through a HCT system extending throughout the region. It is imperative to communicate the urgency of beginning its implementation now and not at a later time.

With the implementation of the envisioned HCT system that includes integrated multimodal components with effective connection and circulation linkages, Houston will be a world-class city on a par with the other largest and most prominent cities of the world. Fulfilling this vision is essential for Houston's future. It cannot wait for the next generation of leadership to act. It must begin now.

APPENDICES

Appendix A Service Concepts for High Capacity Transit

Appendix B Estimation of Peak Passenger Flows at High Capacity Transit Stations for First-Mile/Last-Mile Transit Capacity Assessment

Appendix C Urban District Automated Circulator and FM/LM Systems Deployed on Grade-Separated Transitways

Appendix D Conceptual Station Configurations Suitable for New Dynamic Operating Concepts With AV Transit Service

Appendix E Capacity Improvements to the Railroad Network Necessary for Passenger Rail Service

The Executive Summary and the Appendices of this Opinion Paper have been published as a separate documents and are available on requested from H-GAC