Appendix B

Houston's University District AV Transit Circulator System Study – Phase 1 Physical Planning and Phase 2 Operational Analysis

Appendix B begins with the background planning and strategic approach to the AV project from initial discussions in 2017. The project was viewed as a University District encompassing both TSU and University of Houston. Project demonstration funding was provided by the Metropolitan Transit Authority for the TSU Tiger Walk project. This appendix includes early considerations of the University District leading to the TSU Tiger Walk project, then describes elements of the TSU AV project, and ends with a prospectus of Future AV implementation using information learned from the TSU demonstration project. This appendix was compiled and originally submitted as a Technical Memorandum II and is a standalone report. It is supplemental to the TSU AV Demonstration Shuttle findings. References to Technical Memorandum II may be seen throughout the report.

Houston's University District AV Transit Circulator System Study – Phase 1 Physical Planning and Phase 2 Operational Analysis

APPENDIX B

Texas Southern University
Center for Transportation Training and Research

Houston's University District AV Transit Circulator System Study – Phase 1 Physical Planning and Phase 2 Operational Analysis

APPENDIX B

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APPENDIX B

Section 1 University District AV Transit – A Prototype of AV Circulator Systems in Urban Districts, University and Medical Campuses, and Major Activity Centers

TSU's Center for Transportation Training and Research (CTTR) served as the Principal Investigator for a TRB study performed during the 2015-2017 time period which assessed the implications of deploying automated/autonomous vehicle (AV) technology in transit applications[1]. From this early thinking on AV transit operations and the benefits of early deployments within a semi-protected environment, the first concept for a University District AV Transit Circulator was developed.

The early concept for a district-wide automated transit circulator was envisioned to occur in several stages of development, beginning on the TSU campus and subsequently extending off of the campus to reach the light rail station on the western edge of the University of Houston campus. The interest of Houston METRO was gained in the AV transit project in light of the provision of first-mile/last-mile connections to their existing high capacity transit system at the Purple Line LRT Station at the edge of Univ. of Houston campus.

Figure 1-1 illustrates this functional application of AV "microtransit" using relatively small transit vehicles like the EasyMile EZ10 vehicles which would circulate within urban districts and major activity centers similar to the University District, and which connect with regional transit at intermodal stations. The illustration in this figure was developed by H-GAC staff in concert with TSU's work in support of the H-GAC High Capacity Task Force in 2018 and 2019[2].

The conceptual development phases for the University District also provide for a subsequent Phase 3 deployment that is planned to connect the AV Shuttle Phase 1 and 2 routes with a further extension to reach the Eastwood Transit Center, as shown in **Figure 1-2**. This later extension is anticipated to be deployed within the near to medium term. The timing of Phase 3 deployment will be determined after the shuttle vehicles and operational system has proven its safe and efficient operation in mixed traffic flows along city streets in Phase 2. As a continuing research initiative, the Phase 2 operations will begin with 12 mph maximum operating speeds, whereas the Phase 3 extension to Eastwood will require the

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1 https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3935

2 The summary report of the High Capacity Transit Task Force can be accessed through the web link given below. Note that the illustration was prepared by H-GAC and can be found in Appendix A of the Summary Report. http://www.h-gac.com/high-capacity-transit-task-force/high-capacity-transit-summary-report.aspx

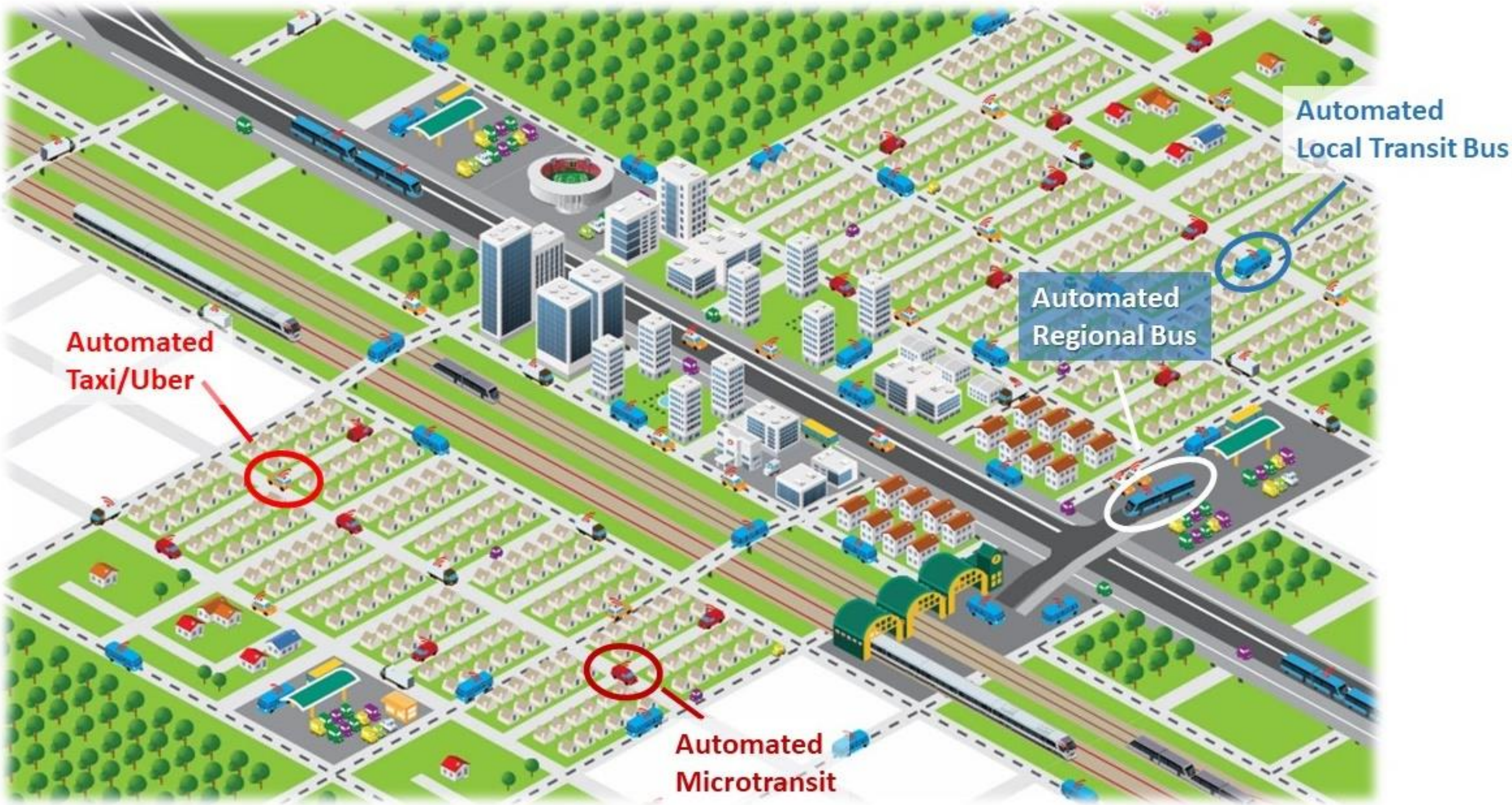


Figure 1-1 AV Transit Circulator System Connecting Urban Districts and Major Activity Centers to Regional High Capacity Transit

Source: Houston-Galveston Area Council

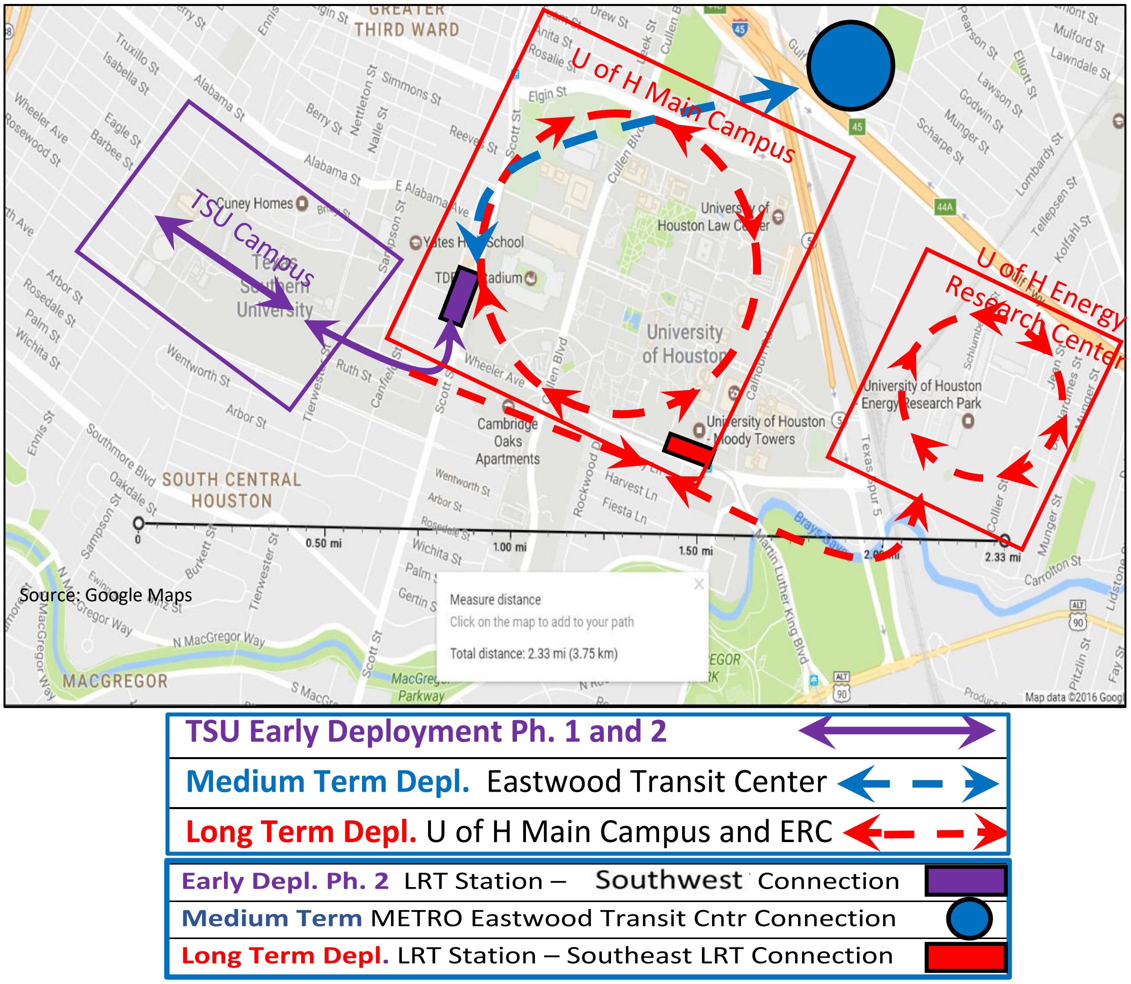


Figure 1-2 Overall Conceptual Plan for the University District AV Transit Circulator System Providing Both Fixed Route Shuttle and Demand-Response AV Transport Services

vehicles to have matured to the point where an operating speed of 20 mph has been proven as safe and dependable.

Phase 2 planning has been underway since late 2018, and a preferred route alignment has now been established through consultation between Houston METRO, TSU, City of Houston, U of H and METRO's AV contractor – the team of First Transit with the vehicle manufacturer, EasyMile. **Figure 1-3** shows the preferred route that is being activity assessed by the project team, as of the date of this report.

The steps necessary to provide for the mitigation of safety risks have been defined for this Phase 2 preferred route, with particular attention having been paid to the two intersections shown in the figure. Intersection 1 is the signalized intersection of Wheeler Ave. and Scott Street, and Intersection 2 is the junction of Wheeler Ave. and Cougar Place where the crossing of the LRT line will occur. This second intersection currently only has crossing arm protection of the LRT tracks, but the safety assessment of the future Phase 2 deployment has resulted in a recommendation to add other traffic control features, such as a three-way stop sign and of vehicle-to-infrastructure (V2I) communications links.

In addition to these safety related infrastructure features and as ongoing research of interest to Houston METRO, the University of Houston and Texas Southern University, concepts for R&D initiatives have been defined which would advance the development of research oriented testing and evaluation of highly advanced intelligent infrastructure at the two major intersections. At those locations, the prospect of implementing smart intersection capability is under consideration. As currently conceived, the project would deploy advanced sensing technology applications, AI-based monitoring and perception .of potential operational hazards in real time, and related command and control aspects necessary to protect the AV transit vehicles from entering unsafe situations in mixed traffic operations at these locations. If adequate grant funding is found to support these research initiatives, the intersections identified in **Figure 1-3** would become some of the first in the world to have this "smart" infrastructure technology installed and tested in association with an active AV deployment.

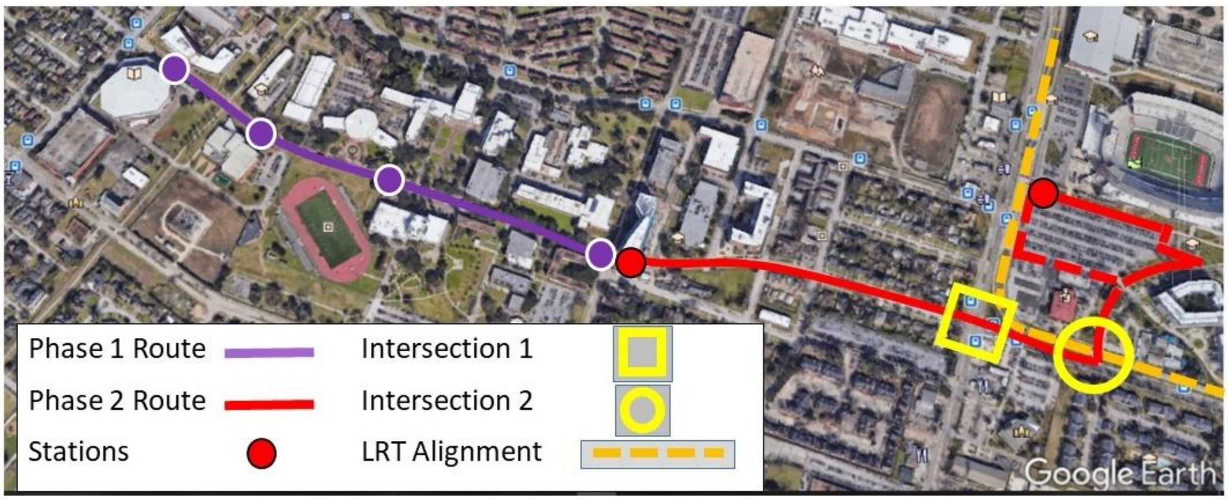


Figure 1-3 University District AV Transit Circulator Preferred Phase 2 Alignment with Passenger Stations at East End of TSU's Tiger Walk and Adjacent to METRO Purple Line Station

The Houston-Galveston Area Council (H-GAC) is preparing for AV transit applications in many urban districts and town center across the region, and this is represented in the latest 2015 Regional Transportation Plan. Houston METRO is leading the charge on the deployment of advanced technology through their sponsorship of the University District AV Transit Circulator System, as well as their intent to create a gradual conversion of the regional bus system – currently operating along about 100 miles of HOV lanes placed in the middle of the extensive freeway system – to AV bus technology. In addition, the METRO Next development plan recently approved by voters will deploy a number of advanced BRT and arterial street bus systems, all of which are candidates for conversion to AV transit as the technology matures in the coming years.

The University District Phase 1 and Phase 2 AV Shuttle projects are the precursor to the future of transit in Houston. They form a true prototype of what the future holds for a fully automated system of autonomous, unmanned transit vehicles operating within the bounds of a local district, campus or major activity center. When this advanced transit technology is integrated into a comprehensive multi-modal transit system, it will be capable of providing both quick and convenient internal district circulation, as well as first-mile/last-mile connections to regional high capacity transit.

These AV "microtransit" circulation systems are envisioned to provide both fixed route service similar to local bus routes, as well as on-demand service with travel routes continuously and dynamically adjusted by an automated supervisory control and dispatching system. Conceptually, the ultimate capability of this technology will be able to provide direct point-to-point travel that fits transit riders' specific origin/destination trip patterns, much like an "autonomous taxi".

Section 2 Phase 1 Deployment – Texas Southern University Campus AV Shuttle

Automated Vehicle (AV) technology, when applied with low speed electric shuttles operating as a transit system constrained to a geofenced area on a fixed route, is the simplest of AV applications envisioned for deployment in the near term. Further, the application of technology that is sometimes referred to as automated electric shuttles – when deployed in an environment protected from other roadway vehicles – has been recognized by the National Highway Traffic Safety Administration (NHTSA) as satisfying their criteria for a "Box 7" category of Research, Testing and Demonstration applications. With this special category of a specific operational environment, NHTSA approved the Phase 1 TSU AV Shuttle project for operation based on the First Transit application made under the special Box 7 category.

However, the relative simplicity of the AV Shuttle operations along Tiger Walk is affected by the complexities of operating within the pedestrian environment. Early assessment of the AV Shuttle was accomplished over the first few months of operation in the summer of 2019. During that time, the single vehicle was operating during the summer session of the TSU campus, with a relatively low level of student activity. Even with this reduced ridership demand condition, assessments of operations have resulted in some changes to the route alignment.

These and other physical and operational planning factors assessed during the early period of operations are discussed below.

2.1 Introduction to Phase 1 TSU Shuttle Physical Planning Studies

This initial stage of implementation was envisioned to comprise a simple shuttle vehicle operating within the pedestrian facility known as the "Tiger Walk", as in **Figure 2-1**. Tiger Walk is a ½ mile long facility which is aligned east and west through the of Texas Southern University campus, comprising the former right-of-way of Wheeler Avenue. The original route concept considered the simplicity of the functional task of moving students, faculty and staff along the linear pedestrian facility, protected from other vehicular traffic other than on-campus electric carts that also move along the facility.

Figure 2-2 shows several photographs of the Tiger Walk environment found to be suitable for the implementation of the AV Shuttle System as Phase 1 of the University District AV Transit Circulator deployment. **Figure 2-3** has photographs taken during the initial commissioning period and following the public "ribbon cutting" ceremonies on June 19, 2019.

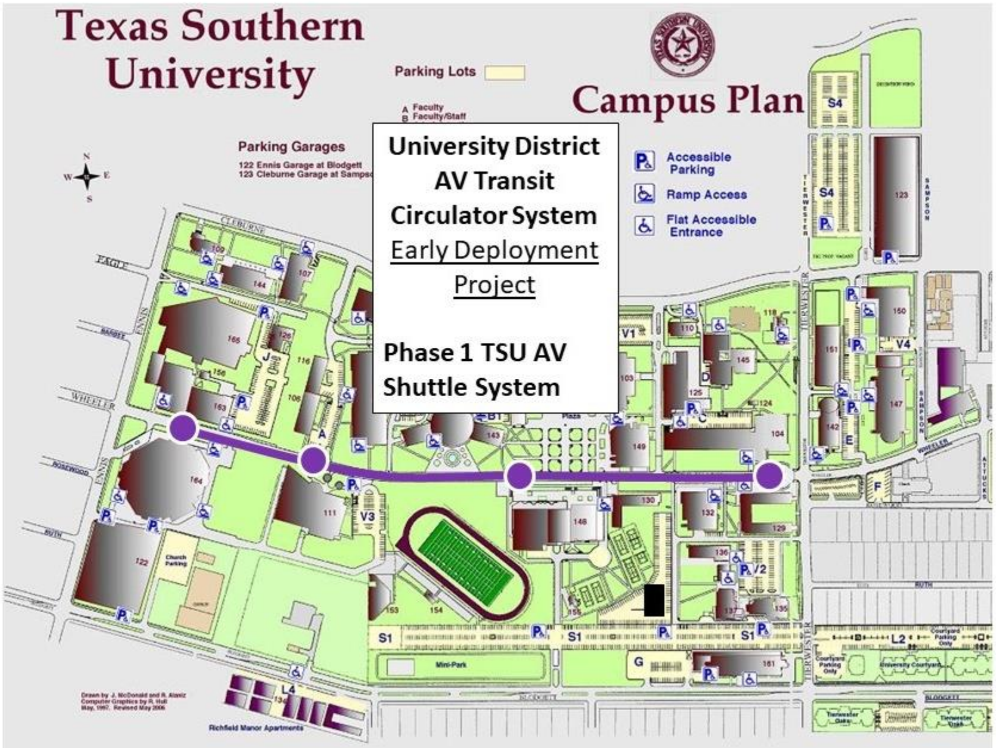


Figure 2-1 Early Deployment Phase 1 Along Tiger Walk

2.2 Automated Vehicle Technology Considerations

There were several important aspects of vehicle technology that were considered in the early planning of the AV Shuttle Phase 1 deployment on the TSU campus when the system was still conceptual. The first aspect concerned the vehicle's battery-electric propulsion system and the issue of electric vehicle operational range due to battery–charge limitation – a significant matter for electric vehicles in transit service. The second aspect was whether or not the vehicle would be configured for bi-directional operation and whether there are passenger boarding doors on only one-side or on both sides of the vehicle. Both aspects are addressed below in terms of the final design utilized in the Phase 1 deployment of the EasyMile vehicle.

There is a third aspect of vehicle technology which impacts the station configuration, and the vehicle's design for how it would berth at the station boarding area. This third aspect of station berthing and the impacts on possible station configurations is discussed later in this section.

Battery Charging Optional Designs – The use of battery-electric vehicle propulsion was found to be a common feature of the AV Shuttle vehicle technologies that were considered to be candidates for the TSU AV Shuttle project, both for the early Phase 1 deployment and for the long term deployment. This led to an assessment of the optional fleet and facilities design concepts that provide the means to charge batteries of the vehicles when operations are sustained throughout the day.

See also the discussion of Energy Consumption and the factors affecting batter discharge in Section 2.5.

Figure 2-2 TSU Tiger Walk from West End (upper left) to East End (lower right)

Figure 2-3 Early Test, Commissioning and Official Ribbon Cutting Activities of the EasyMile Shuttle

Three approaches were found in industry for battery charging during the operating day, each with different infrastructure needed for the associated battery charging rates. This transition to battery electric propulsion is not just a hardware issue. It also involves the operational approach to allow for adequate vehicle charging time, combined with the design requirements for the support facilities where battery charging will occur. These different approaches to battery charging have a direct bearing on operating fleet size, support facilities and electric battery charging infrastructure.

For the initial demonstration pilot of Phase 1 with only a single vehicle in operation, the approach to battery charging was to establish an operating plan for the EasyMile vehicle which limited the number of service hours. This plan allowed the vehicle to return to the maintenance bay for battery charging after the morning service period. During this operational hiatus in the middle of the day, the vehicle's power cord was plugged into a charging station for several hours, after which it was returned to service for the late afternoon and evening hours. With the natural reduction of student activity on campus during the middle afternoon hours, this cessation of service for several hours to allow for vehicle battery charging was possible to accomplish even with only one vehicle in the operating fleet.

For multi-vehicle fleet operations that continue without cessation throughout the day, this requirement to completely remove a vehicle from service to charge its batteries becomes a major factor driving the necessary fleet size. These fleet size implications would have corresponding capital and operating costs impacts. The additional cost can be partially mitigated by the provision of conventional charging equipment with a moderately fast charge rate capability located in the maintenance and storage bays, or even onboard the vehicle. The capital costs for charging provisions is the lowest for this approach. For the ½ mile long Phase 1 route, this was the ultimately the selected option, and it is discussed further at the end of this Section 2.

A second approach considered was to utilize an AV technology that would allow inductive power transfer to the vehicle such that batteries can be charged while stopped in the stations during the short dwell times of about 1 minute. This approach requires charging infrastructure to be installed in the roadway/station berths, which can be a significant capital cost in many situations.

A third approach considered was to create special, dedicated storage locations spaced throughout the operating route's service area. For the initial Phase 1 route configuration of a single vehicle shuttling along a route of only ½ mile length, this option proved to be unnecessary. However, it was felt that this approach would be important to consider further when the future University District's conceptual operating plan envisions the extensive use of automated on-demand dispatching and/or dynamic adjustments to the operating fleet size as ridership demands rise and fall throughout the day. There would be significant periods of time when any given vehicle would be dormant until ridership demand conditions increase, requiring it to be dispatched back into service. During those times when vehicles are dormant and waiting for a dispatch order from the supervisory control system, they could be sent to a dedicated storage area where the vehicle's batteries can be charged.

For a large scale system such as the ultimate University District AV Transit Circulator System, the advantage of a dedicated storage area charging approach is that the power infrastructure would be more cost effectively provided in a very few suitably located and equipped storage areas. Further, special charging stations can be designed at these special locations which allow high speed, high current charging of one or more vehicles at the same time, and with charging occurring automatically with suitable operations personnel oversight.

Vehicle Configuration – Also considered in the early planning were the vehicle design characteristics with respect to door configuration, and the associated propulsion system capability to operate bi-directionally (i.e., to reverse direction by reversing the head-end of the vehicle without turning it 180 degrees). This design configuration aspect affects the route alignment and the station locations, and it was evaluated primarily with respect to the Phase 1 operations. It does, however, have significant implications when considering the future AV transit applications within the larger University District area.

The key vehicle characteristics that were considered during the early conceptual development and pre-procurement planning, alignment planning, and further assessed through the initial EasyMile vehicle testing and commissioning were as follows:

1. Vehicle propulsion and automated driving control system capabilities for unidirectional operations or bidirectional operations.
2. Vehicle passenger boarding door configuration, with either doors on only on one side of the vehicle or doors on both sides of the vehicle.
3. Vehicle turning radius.
4. Provisions for either ramp deployment for wheelchair access, or precision docking for raised platform level-entry of wheelchairs.

The fundamental importance of these vehicle design features was that they had a significant impact on the original concept of route operations for passenger service along a corridor. The first operational concept assumed a unidirectional vehicle would reverse its travel direction through a 180 degree turn at the end of the Tiger Walk corridor before or after the end-of-line station stop. Further, the studies considered how the operation of this operational approach for a unidirectional propulsion system had a significant effect on station locations, when combined with a vehicle design with doors on only one side of the vehicle. The operational conditions that resulted required the placement of station boarding areas on opposite sides of the Tiger Walk at each station location, depending on the desired direction of travel. This route alignment issue is addressed below as a site planning matter.

Vehicle design features are discussed below with regard to the associated implications for route alignment and station location.

2.3 Phase 1 Alignment and Station Locations

The ability to change the route alignment and the station locations with what is generally only a vehicle software change is one of the important benefits of autonomous AV transit technology. This capability proved to be very advantageous during Phase 1.

Route Alignment – The route alignment for the Phase 1 single vehicle's operation had several stages of development and assessment. In the initial conceptual alignment, the system configuration was based on the placement of stations in the center of the Tiger Walk alignment, using raised platforms which for fixed guideway transit is typically called a "center platform" station configuration. However, the cost of building these platform structures was an expense for the Phase 1 demonstration pilot that had not been included in METRO's original budget planning.

Additionally, by the time that the procurement had selected the First Transit/EasyMile team as the Phase 1 contractor, the identification of the EasyMile EZ10 vehicle provided the option to use the integral-design of a wheelchair ramp – as discussed below. This feature allowed the concern about wheelchair user access to be satisfied without requiring a raised platform design.

During the early Phase 1 of vehicle operational testing, each alternative alignment had further adjustments made and evaluated to best match vehicle features and operational limitations with the route alignment and the associated configuration of station locations. These alignment and station configuration alternatives that were investigated are discussed in some detail in the next sub-section addressing operational route configurations.

The Phase 1 EasyMile EZ10 Gen2 vehicle deployed in May of 2019 for the Phase 1 project. This vehicle had bi-directional propulsion capabilities and was configured with doors on only one side of the vehicle. The turning radius was such that the vehicle could make a complete turn without reversing its head-end within the 42' width of the Tiger Walk at the west end (see **Figure 2-4)**. Further, the vehicle can easily travel through the driveway loop existing just beyond the east end of the Tiger Walk (see **Figure 2-5**). Refer also to **Exhibit A** for additional technical specifications of the EasyMile EZ10 Gen2 vehicle.

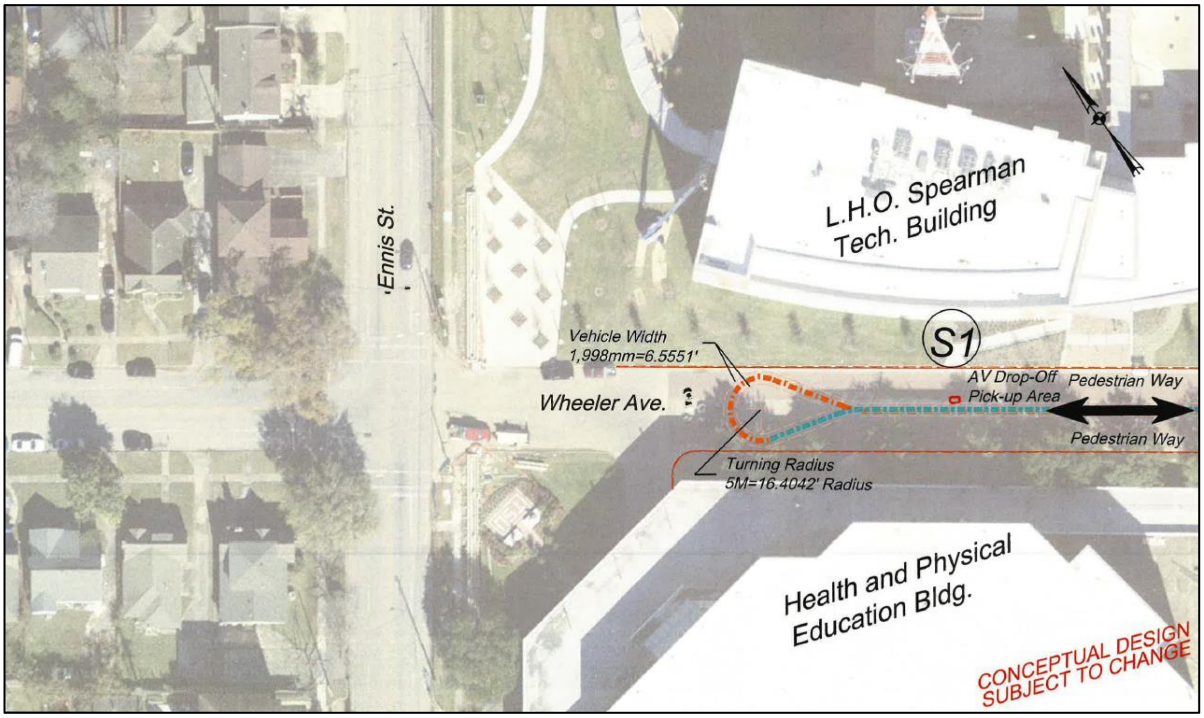


Figure 2-4 180 Degree Turn at the West End of the Tiger Walk

Source: Houston METRO

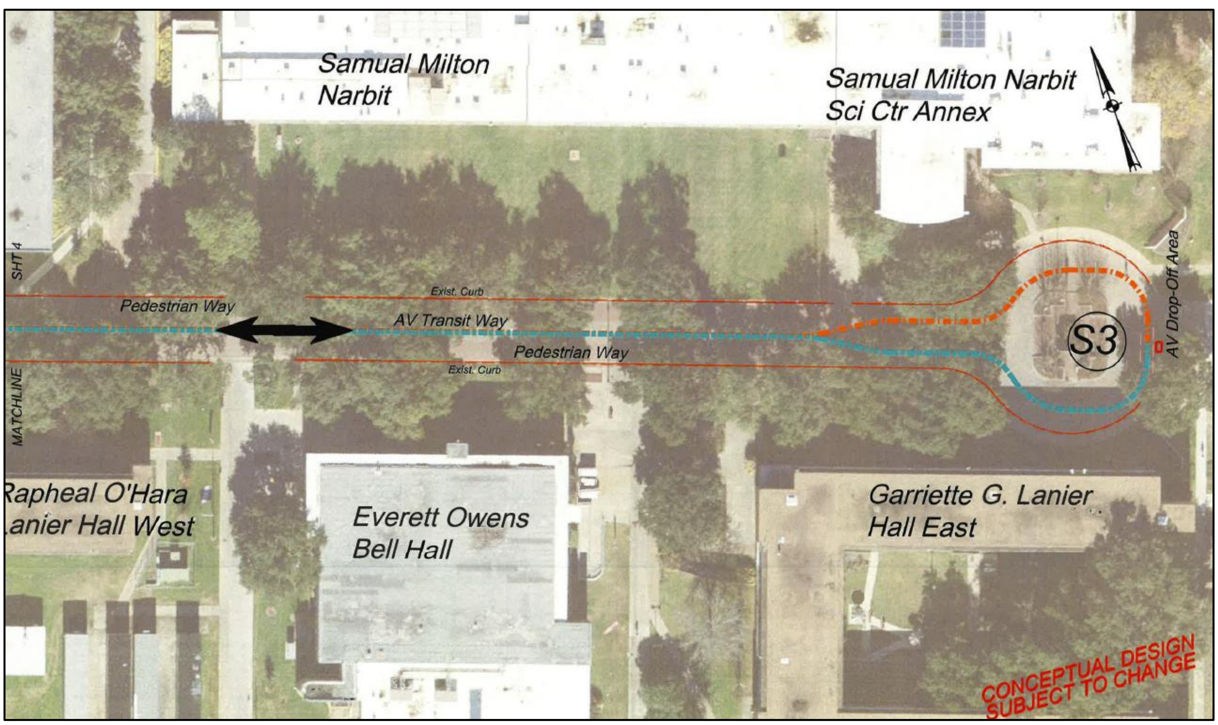


Figure 2-5 180 Degree Turn at the East End of Tiger Walk

Source: Houston METRO

Station Placement – The assessment of trip generation points within the campus was the basis for the initial placement of station locations, and this assessment became a continuing process as optimum station stopping and boarding locations were studied. Each of the major buildings on campus has its own unique trip generation characteristics, with the buildings comprising classroom facilities being subject to temporal peaks and valleys in accord with the class schedules.

As the Phase 1 Demonstration Pilot began operation, the precise location of the station stopping points became a process of testing vehicle capabilities and assessing operational impacts on the pedestrian environment. The combination of highest trip generation locations on the campus, space accommodations for passenger waiting/queueing and vehicle stopping locations was under constant evaluation throughout the first few months of operations. The stations were originally planned for four locations, but as initial service began the number of station locations was reduced three locations.

In addition, various operating route configurations were tested that changed the vehicle orientation with respect to its single-side door placement. When the vehicle was turned by traveling around a 180 degree loop at the end of Tiger Walk, it changed the practical use of a single boarding location at each station for both east and west bound trips. Instead, each intermediate station required a boarding location on the south side of the 40 foot wide pedestrian facility for eastbound trips as well as a boarding location on the north side of Tiger Walk for westbound trips due to the vehicle door location switching sides for eastbound vs. westbound trips.

Station Access – Access to the boarding locations was a key parameter in the assessment of the various boarding location placements as the different operating route alignments were implemented (see discussion below). Knowing that access for the disabled is of very high importance, this aspect of station access has been paramount in the assessments.

The early concept development stage originally placed wheelchair access ramps within the center station platform design, as is common for Houston METRO's light rail system station designs. This early concept, however, proved impractical for this Phase 1 Demonstration Pilot (see further discussion below).

Features of the EasyMile GEN2 vehicle technology, with its wheelchair access ramp integrated into the vehicle chassis design, were evaluated during the initial phase. **Figure 2-6** shows the vehicle ramp deployment being tested when the vehicle first arrived at the TSU campus and before operations began. Note that the ramp angle of incline is a function of the differential height between the passenger compartment floor level and the level of the boarding area surface. Consideration of station locations where there is a natural raised elevation above the roadway surface level were considered since they beneficially affect this ramp incline level, thereby making it easier for a person in a wheelchair to access the vehicle passenger compartment without assistance.

Other considerations given to station access accommodations concerned the information in the form of signage that indicates the stopping point of the shuttle vehicle. Although the placement of static signs alone does not satisfy ADA regulations for the sight disabled passengers, the signage shown in **Figure 2-7** was believed to be adequate for this initial demonstration pilot phase of the University District AV transit deployment because a safety attendant was present on the vehicle at all times. As with the assistance of mobility disabled passengers who need the wheelchair access ramp deployed and possibly other assistance to enter or exit the vehicle from the boarding area, the onboard attendant was always present to provide this assistance when needed during Phase 1 operations.

Boarding/Alighting Area Considerations – Three station configurations were considered for the TSU Shuttle, with the first being a raised platform located in the center of the Tiger Walk. The plan for this early station concept was developed by Houston METRO and is shown in **Figure 2-8.** This concept was based on a "center platform" configuration that is common for fixed guideway transit systems.

A major advantage of this raised platform station concept is that with a vehicle berthed with sufficient precision at the platform edge, it would allow a wheel chair to roll onto the vehicle directly from the platform. This raised platform, however, would also require the vehicle to approach the platform and make a precise stop with respect to the vehicle door threshold and the raised platform edge – a capability that is not universally present among the AV shuttle vehicle developers[3].

Even without the "precision docking" capability where the vehicle has to have its "lateral" location precisely determined, the planning studies and operational tests found that longitudinally precision stopping feature was still essential such that, as a minimum, a vehicle must stop with sufficient accuracy to safely deploy its ramp at the specific location where a person in a wheelchair was waiting to board.

The raised center-platform station configuration was not developed beyond the conceptual level for Phase 1. As noted above, this station platform configuration would have required unplanned capital expenditure to construct the raised platform structure. Further, the raised platform would itself have to include an ADA compliant wheelchair ramp system built into the structure in order to reach the level of the platform necessary for boarding purposes, as shown in an original concept drawing in the figure.

Other considerations that were determined to be important for the boarding area were the sufficiency of the available space to accommodate passengers queuing to board when the vehicle arrived at the station stop, as well as suitable access to the waiting area for wheelchairs in accord with ADA laws.

[3] Reference the discussion of "precision docking" in NCHRP 20-102-(02), Working Paper#1 Automated Vehicle Technology Deployment Scenarios for Public Transit, Appendix A that discusses this design feature.
http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-102(02)_WP1_AV_Transit_Deployment_Scenarios.pdf

Figure 2-6 Testing of Vehicle Wheelchair Access Ramp Deployment

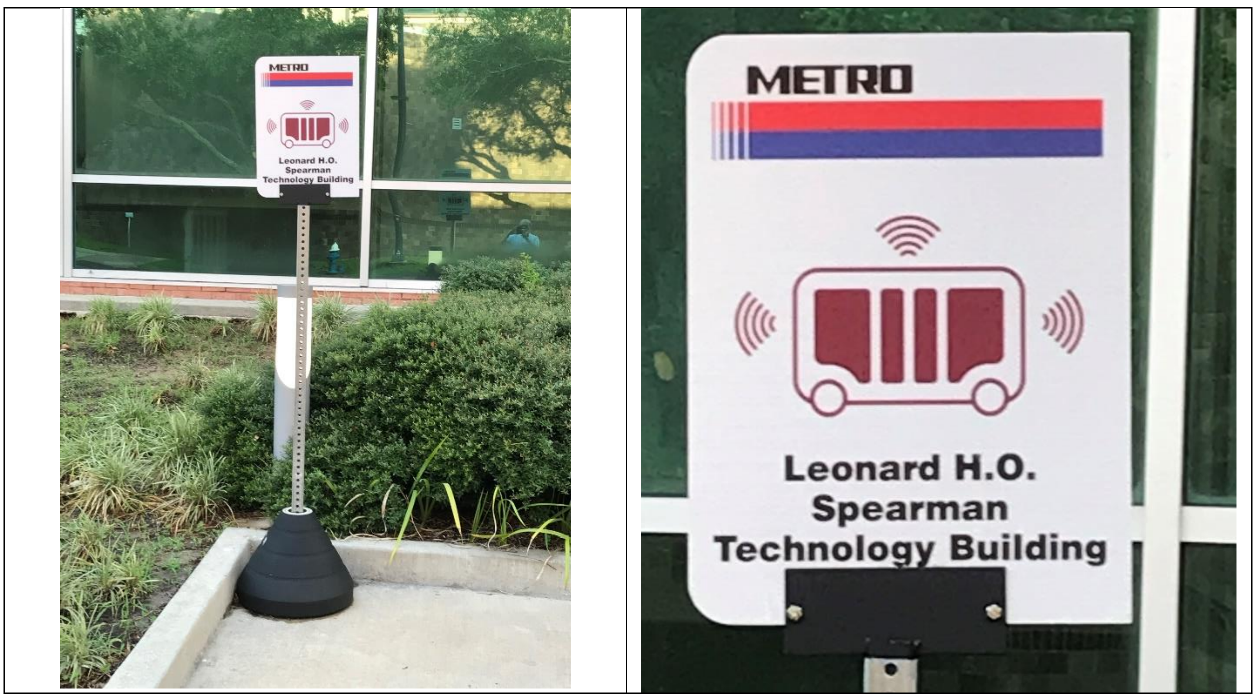


Figure 2-7 Phase 1 Demonstration Pilot AV Shuttle Station Stop Signage

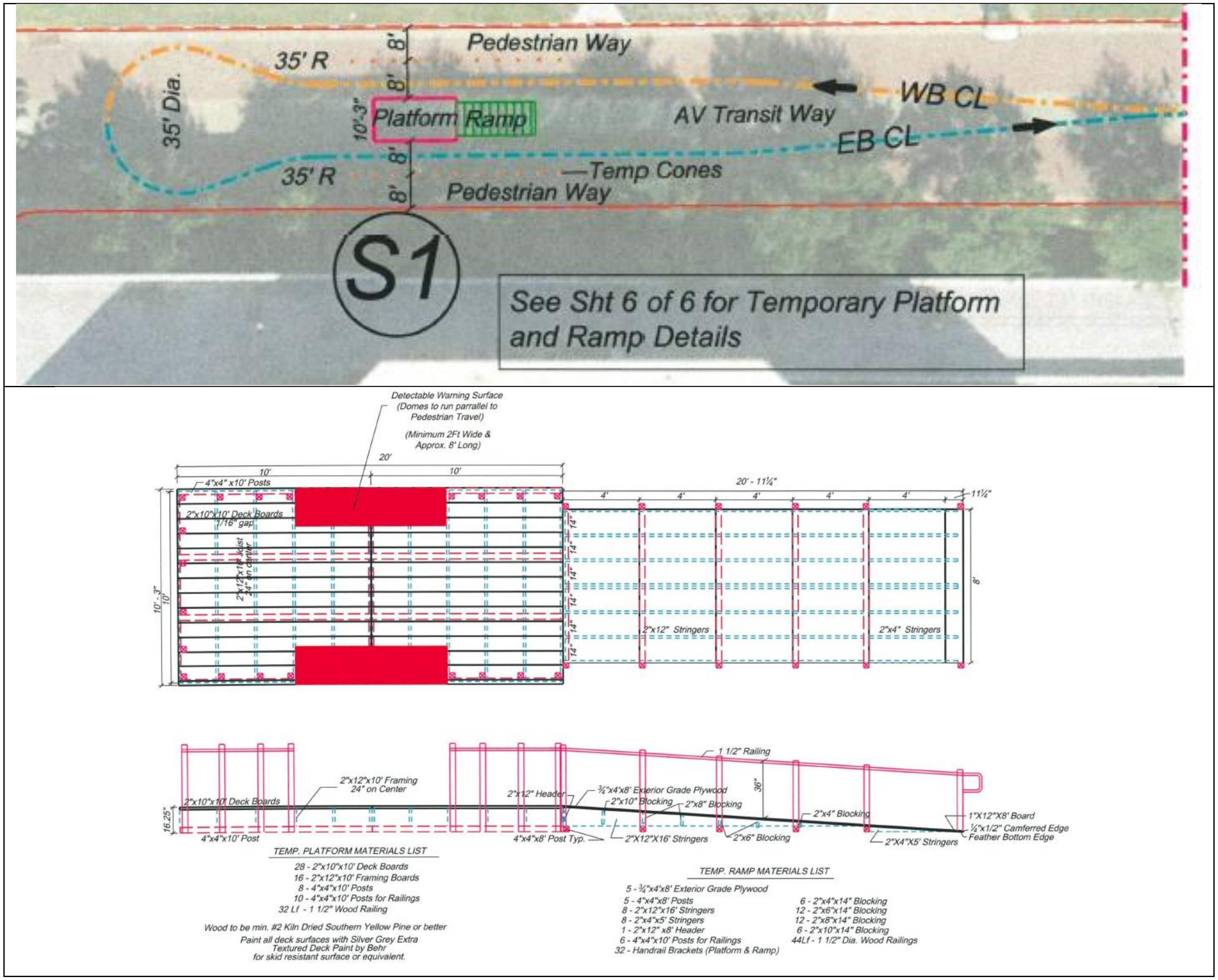


Figure 2-8 Design Concept for Raised Center Platform Station Concept at West End of Tiger Walk

Source: Houston METRO

2.4 Operational Route Configuration

A variety of operational route configurations were evaluated through concept studies and through actual operational testing during the early months of the Phase 1 deployment in passenger service. The general corridor alignment along the TSU Tiger Walk was maintained as the basic service concept throughout the route configuration evaluation process. However, within that generally linear corridor different route configurations were still possible to operate. The following terminology that indicates the way the vehicles progress through the alignment was defined for purposes of this report:

- Loop Configuration – the vehicle operates continuously in a unidirectional mode with a 180 degree "loop" maneuver at each end to reverse its direction.
- Shuttle Configuration – the vehicle operates in a bi-directional mode with a reversal of the head-end at each end-of-line station to travel in the opposite direction along the linear corridor.

Center Lane Loop-Route Configuration – When the procurement process identified EasyMile's EZ 10 vehicle as the selected technology, the vehicle characteristics and operational capabilities gave more specificity to the route planning process. The initial plan for the operating route with the EasyMile vehicle was that the vehicle would travel along the center lane with a loop configuration operations, and with the pedestrian "lanes" along each side. In this initial operating route configuration, as shown in the photographs of **Figure 2-3** above, the vehicle remained in the center lane throughout the length of Tiger Walk. Then to create a loop route configuration in which the vehicle was operating with uni-directional propulsion, the vehicle steered itself through a 180 degree turn at each end.

The "station stops" were also in the center lane, as shown in the **Figure 2-3**, but without the raised center platform discussed above. Instead, the vehicle simply came to a stop within the center lane and opened its doors to allow passenger boarding and alighting to occur.

One issue was soon realized, however, due to the stations stops occurring where all passengers board with the vehicle in the center lane. Each time the wheelchair access ramp was deployed, it extended into the pedestrian lane creating a potential hazardous conditions for distracted pedestrians.

Another consideration with this initial loop configuration of the operating route was the alternating sides of the vehicle door location for eastbound and westbound travel, as discussed above. The result was that passengers waiting to board a westbound trip were directed by signage to wait on the south side of Tiger Walk, and passenger waiting to board an eastbound trip were directed to wait on the north side of Tiger Walk. In this initial configuration, the waiting area at each "station stop" was defined to be along the side edges of the Tiger Walk where signs were placed to encourage queuing out of the main pedestrian pathway. See **Figure 2-7** for an example of this signage.

Center Lane Loop-Route Configuration with Side Station Stop Diversions – As a potential improvement to the station boarding process and to provide a better location for wheelchair ramp deployment (i.e., mitigating the risks with ramp deployment into the active pedestrian lane), the route was reprogrammed to turn the vehicle out of the center lane as it approached the station boarding location in order to bring it to the side of the Tiger Walk right-of-way.

Figure 2-9 shows this stopping location at the side of the Tiger Walk alignment that corresponds to the center stopping location of the alternative route. This location was chosen because it provides direct vehicle access from the ADA ramp to and from the main doorway of the Spearman Technology Building.

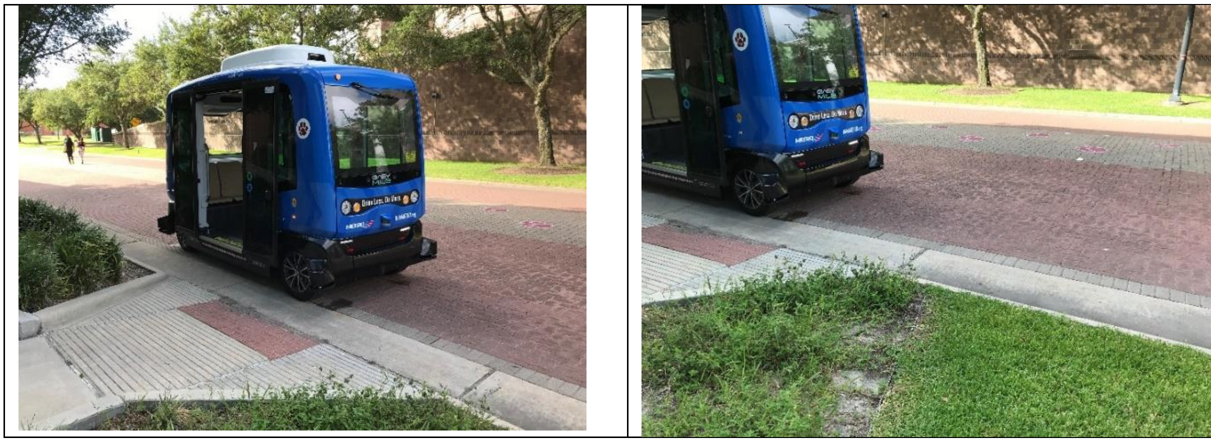
Figure 2-9 Station Stopping Location at the North Side of the Tiger Walk ROW at the Bottom of the ADA Ramp to the Spearman Technology Building

Although this operating configuration was definitely better for passenger boarding purposes, especially with respect to the wheelchair access ramp deployment and the station waiting queue location, it soon became apparent that a different kind of hazard was being introduced by this route alignment. The hazard resulted from the fact that college students often walk their attention distracted by their mobile phones, and as a result they are at times oblivious to their surrounding environment as they walk. This alignment in which the vehicle would steer out of the center travel lane to reach stations at the side of the ROW, when combined with the attention deficit of college students, created a hazardous condition each time the vehicle turned across the pedestrian lane to reach the station stopping point.

As a result, a plan was devised to add lane markings to indicate locations where the shuttle vehicle would divert from the center lane to reach its programmed stopping point at the edge of the Tiger Walk. This would provide a surface indication that the pedestrian was crossing the turnout lane of the shuttle. But this lane marking plan was never implemented due to another issue that arose with this operating route alignment.

As the shuttle route in the center lane with diversion to side station locations was first operated over a several week period of time, the sensitivity of the vehicle's sensor stack began to create issues with false readings of objects in the vehicle's travel trajectory. A characteristic of the EasyMile vehicle technology that had been noted in low speed AV shuttle operations in project locations elsewhere in the United States was that the Lidar sensors scanning the surface of the roadways were very sensitive, and that a false reading of an object in the vehicle's path caused by adjacent vegetation was a common cause of sudden vehicle braking. This proved to be true for the TSU shuttle, as well.

The presence of grass and shrubbery planted along the edges of the Tiger Walk (see **Figure 2-10**) caused periodic problems when a breeze caused the vegetation to move. This could result in the vehicle initiating an emergency brake and stopping short of its programmed stopping location, which in turn disrupted passenger boarding and alighting. This occasional failure of the vehicle to stop in the proper station berth hampered, In particular, the deployment of the wheelchair access ramp (when necessary).



F***igure 2-10 Example of a Misaligned Vehicle Stopping Location Due to Vegetation Movement Adjacent to the Programmed Station Stop Affecting the Lidar Sensors***

Center Lane Shuttle Alignment with Half Loop Configuration – Based on the hazard conditions and operational problems of the center lane route with diversions to side stations as described above, the alignment was re-evaluated and a route alignment that stays within the center AV Shuttle designated travel lane was considered again for its beneficial deployment. The marking of the center of the Tiger Walk as the dedicated AV shuttle lane was accomplished using typical highway reflectors, as is shown in **Figure 2-11**. This assignment of the shuttle operations to occur only within this lane required that the station stops be in the middle of the Tiger Walk, with the boarding process requiring the passengers to walk to the middle where they can step up into the vehicle (refer to **Figure 2-3** above).

Initially, the route alignment concept was thought best to discontinue the 180 degree turn at the west end of the alignment due to the similar concerns to the vehicle crossing the pedestrian lane. But this concept retained the loop operation at only the east end since it passes through the existing loop road at the end of Tiger Walk under less hazardous conditions and provided a very convenient station stop directly adjacent to the new Library building.

However, the configuration of the vehicle with doors on one side only, combined with the plan to take the vehicle through a 180 degree loop turn at only one end of the route resulted in other problems along the rest of the route. Using the vehicle's bi-directional propulsion capability, reversal of the head-end of the vehicle's travel direction occurred at the west end only after stopping at the Spearman Technology station.

Figure 2-11 Reflective Markers and Colored Tile to Designate the Dedicated AV Shuttle Lane

When traveling back in the eastbound direction, the vehicle had no reversal of its head-end of travel at the opposite end of the shuttle alignment as it passes through the 180 degree loop, which created an a different kind of operational problem. The conditions where the head-end of the vehicle is reversed only one time for each round trip results in the side of the vehicle with the doors being reversed in each subsequent round trip. The boarding location for eastbound travel during round trip circuit #1 would be on the north side of Tiger Walk for a given station. Then the door and the necessary boarding location during the next round trip #2 would be on the south side of the vehicle for eastbound trips. To state the problem simply, the boarding location would reverse at every station each time the vehicle passes. The confusion of which side of the Tiger Walk for waiting passengers to queue on would be a significant impediment to operations. For this reason, this route configuration alternative was never implemented.

Simple Shuttle Route on a Center Lane Alignment – Through these various operating route tests and operational concept studies, the final operating route was determined to be a simple shuttle operation, with the vehicle remaining in the center lane of the Tiger Walk and the head-end of the vehicle being reversed at each end-of-line station stop on the west and the east ends. This simple shuttle route configuration is being referred to by TSU project staff as the "elevator mode" operations.

Locations originally served by the shuttle station stops were the Spearman Technology Building, the Student Center, and the new TSU Library. These three station locations comprised four stops by the vehicle during each round trip, with the vehicle stopping at the middle Student Center station as it travels in either the eastbound or the westbound directions, and with the vehicle door always located on the north side of the vehicle body.

However, a fourth station location was added as operational experience with the Shuttle route was gained, creating 6 station stops in every round trip. **Figure 2-12** shows the final route alignment and station stops that operated throughout the majority of the Phase 1 AV Shuttle Demonstration Pilot project.

Figure 2-12 Simple Shuttle Alignment Determined to be the Optimum Operating Route Alignment for the Phase 1 AV Shuttle Demonstration Pilot

2.5 Phase 1 Storage/Maintenance and Operational Support Facilities

After the selection of the AV Shuttle Contractor team was accomplished and the specific vehicle to be accommodated was known, a process was undertaken to assess the potential locations which could serve as the vehicle storage and operational support facility. It was known by the contract award that a single EasyMile vehicle would be deployed in Phase 1, and the specific power supply requirements for vehicle battery charging was therefore defined in accord with the EasyMile design. The selection of the vehicle storage location involved the TSU Administration, TSU Facilities, TSU Security/Police, Houston METRO and the Contractor team – First Transit/EasyMile.

Accommodation of the vehicle height proved to be one of the most constraining parameters for a suitable storage location, followed by the proximity of the location to the operating route. It is important to recognize that the NHTSA approval to operate takes into full consideration this aspect of proximity and travel path for the vehicle to move between its storage/charging location and the operating route.

Size and Configuration Considerations – The matter of dedicated space to serve as a "maintenance and operations" facility for AV shuttle operations is fundamentally determined by the size of the vehicle fleet. For the single vehicle deployment in the Phase 1 TSU Shuttle project, a substantial variety of spaces were considered. Insight into appropriate facility provisions was gained by this process, in particular with respect to the door size/clearances and functional utility of the vehicle storage location. Multiple location options were considered, and the following lit provides highlights of the factors identified and the lessons learned.

1. Creation of Inexpensive Temporary Storage Space
    - A structurally adequate, weather protected space was deemed necessary for proper care of the vehicle as a fundamentally important criteria by which this option was evaluated.
    - Size of the vehicle was such that premanufactured buildings were deemed impractical because of the cost.
    - A temporary enclosure was considered under a weather protection structural roof over simple parking spaces, with the vehicle storage area created by "soft" tarpaulin walls hung to create a temporary enclosure. .

- Other locations were considered that were not enclosed facilities, but under a roof along an active driveway.
- Conclusion: These "temporary" enclosures were inadequate, primarily for security reasons.

2. Inside a Parking Garage Structure
    - The clearance requirement of over 9 ½ feet necessary for EasyMile vehicle access was too high to clear the 9 ft. standard architectural clearance at the existing driveway entrances at the West Parking Garage structure.
    - Conclusion: Structures designed for automotive use and not for very tall vehicles typically would not have adequate clearances for the EasyMile vehicle.
3. Loading Bay of an Existing Building with Indirect Access
    - A loading bay was evaluated which would require the continued accommodation of the delivery of materials several times a week through this space.
    - Access and egress travel paths between the west end of Tiger Walk and this loading bay location were determined to require the AV Shuttle vehicle to travel one block along a city street on the west side of the campus. This "off-campus" travel path would impose the following challenges:
        - Metro and/or TSU police car escort would probably be required each time the vehicle moved to or from Tiger Walk.
        - The distance of travel between the operating route and the storage location was more than EasyMIle's stipulation of 300 ft. maximum.
        - The travel on a city street in mixed traffic would have placed the NHTSA waiver approval in substantial jeopardy.
4. Vehicle Bay That Could be Dedicated to AV Shuttle Storage
    - A vehicle bay was identified that was being used for stored of materials and equipment, which the TSU Facilities Department offered to make available.
    - The space was provided as a secure storage location for AV Contractor
    - Repairs and modifications to the large rolling door were made allow the door to be remotely operated by an AV shuttle operator from within the vehicle.
    - The space provided ample space and electrical power provisions for the both initial Phase 1 vehicle, as well as space to accommodate more vehicles when Phase 2 begins.

Proximity of Support Facilities to Operating Route – The proximity of the vehicle storage and charging location(s) was an important consideration in the planning of the route and the vehicle maintenance considerations. An EasyMile request to locate the storage within 300 yards of the operating route was able to be accommodated by the North Side Vehicle Bay in the Central Plant facilities.

The ease with which an onboard attendant can drive the vehicle from the operating route to the charging/storage location was understood in the planning phase as having a major impact on the overall operations. In the case of the Phase 1 Demonstration Pilot project, the proximity of the Central Plant location for storage accommodations which satisfied the EasyMile request was a key part of the final decision on the storage location.

The selected vehicle storage location that best satisfied the maintenance and operations facilities requirements for the single AV shuttle vehicle at reasonable expense and accommodation by TSU was the Central Plant vehicle bay, as shown in **Figure 2-13**.

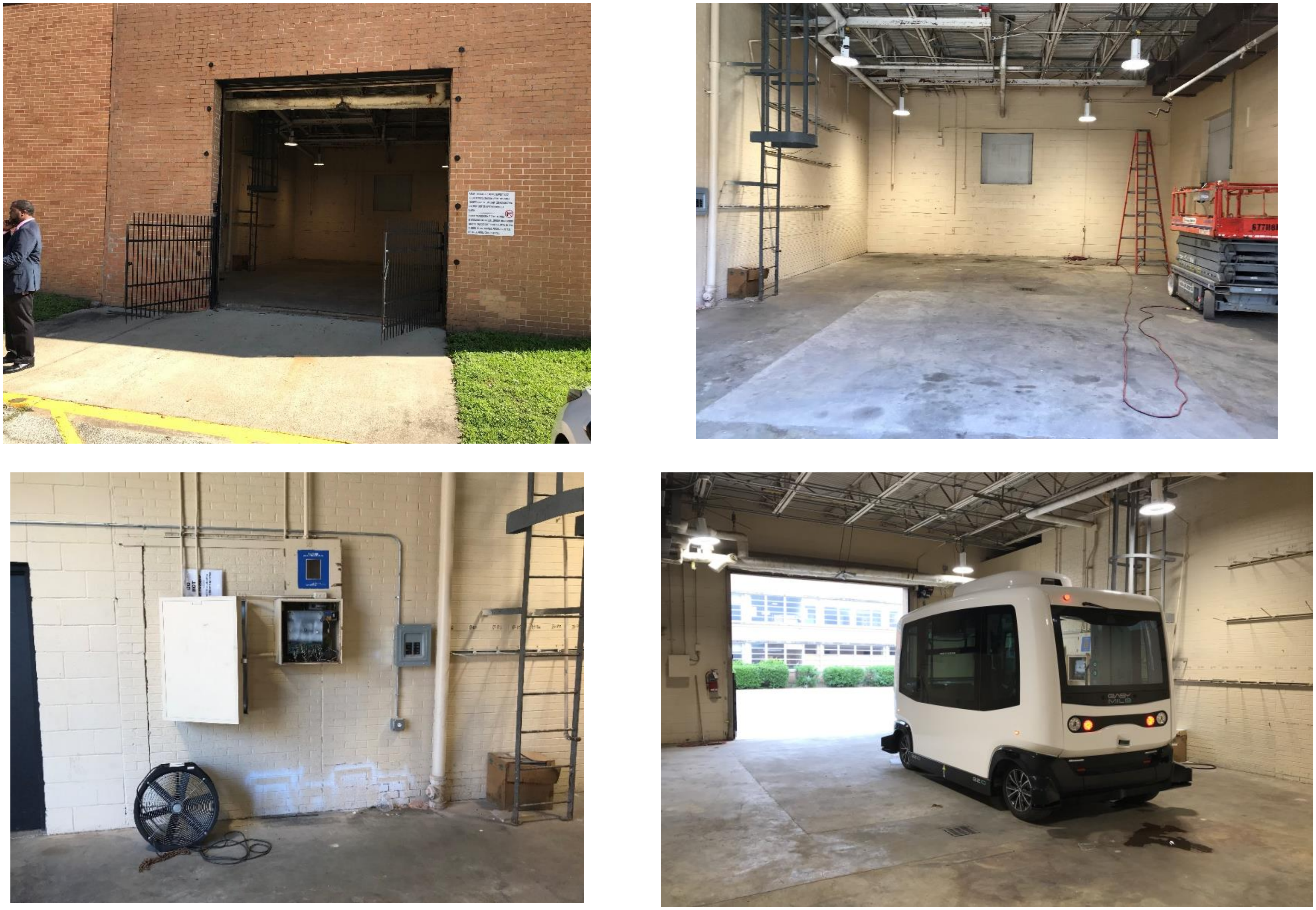


Figure 2-13 Selected Vehicle Storage Locations With Power Supply Provisions to Connect Battery Charging Equipment

Electric Vehicle Charging Accommodations – The power supply requirements that were provided by EasyMile were the basis for assessing the suitability of existing circuits in the Central Plant vehicle bay. For future consideration of battery charging power supplies, the voltage and amperage limitations of available circuits and the power supply would determine whether the charging equipment can accommodate a more beneficial rapid charging rate.

The EasyMile specified electrical provisions specifications for the storage area as a 240VAC 20-40A power supply circuit with a dedicated circuit breaker, and a power receptacle at the charging location to allow the power charging cable from the vehicle to plug a NEMA 14-50R Connector into a compatible female receptacle**.** **Figure 2-13** shows the power supply provisions and the vehicle as it was positioned in its charging location. This power supply was suitable for the EZ10 vehicles' "built-in" battery charger which can accommodate only a slow charging rate.

2.6 Power Consumption Research with Idaho National Laboratory

The limitations to a vehicle's operating range due to the depletion of the vehicle's battery charge is a major point of attention throughout the budding AV transit industry. For the Phase 1 operation it became a major factor in determining the service hours for the single vehicle fleet before recharging of the batteries was required.

This relationship of battery-charge depletion with service hours and range limitation became one of the key areas for which data was collected as part of a federal research study. As the EasyMile vehicle technology deployment was in its initial stages, METRO and TSU were approached with a proposal for a collaborative research endeavor by the Idaho National Laboratory[4] (INL), which is a US Department of Energy lab. The nature of the equipment installed and the associated data collection and analysis are described below.

Power Consumption Data Collection Equipment – The AV power consumption research by INL was accomplished using a special meter which was installed between the vehicle charging plugin receptacle and the breaker panel, as shown in **Figure 2-14**. Their equipment monitored and recorded the electrical power consumed when the vehicle batteries were being charged in the storage facility. A cellular device uploaded the data from the INL equipment each day for processing and analysis at the INL research lab.

From this data the energy consumed, measured in particular as an "energy intensity" value measuring power consumption consumed per mile traveled during the vehicle operations throughout the 2019 summer and fall semesters. The data logging energy meter provided the data tracking of all charging cycles, which was then used in combination with data on the accumulative vehicle-miles traveled each day to assess and quantify the energy use for the specific AV shuttle application.

Power Consumption Research Results – The collaborative effort was undertaken with the Idaho National Laboratory by Houston METRO, TSU's Center for Transportation Training and Research, and the Contractor team to compile the daily field data collected from the Phase 1 TSU Shuttle operations. The research was funded and performed under the auspices of the DOE Vehicle Technologies Office SMART Mobility research program. First Transit operations staff and EasyMile engineering staff were an essential part of the data collection and compilation effort by providing requested data records to INL.

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[4] Mr. Matthew Shirk of the Idaho National Laboratory leads the Energy Consumption research at INL under the DOE Vehicle Technologies Office SMART Mobility research program.

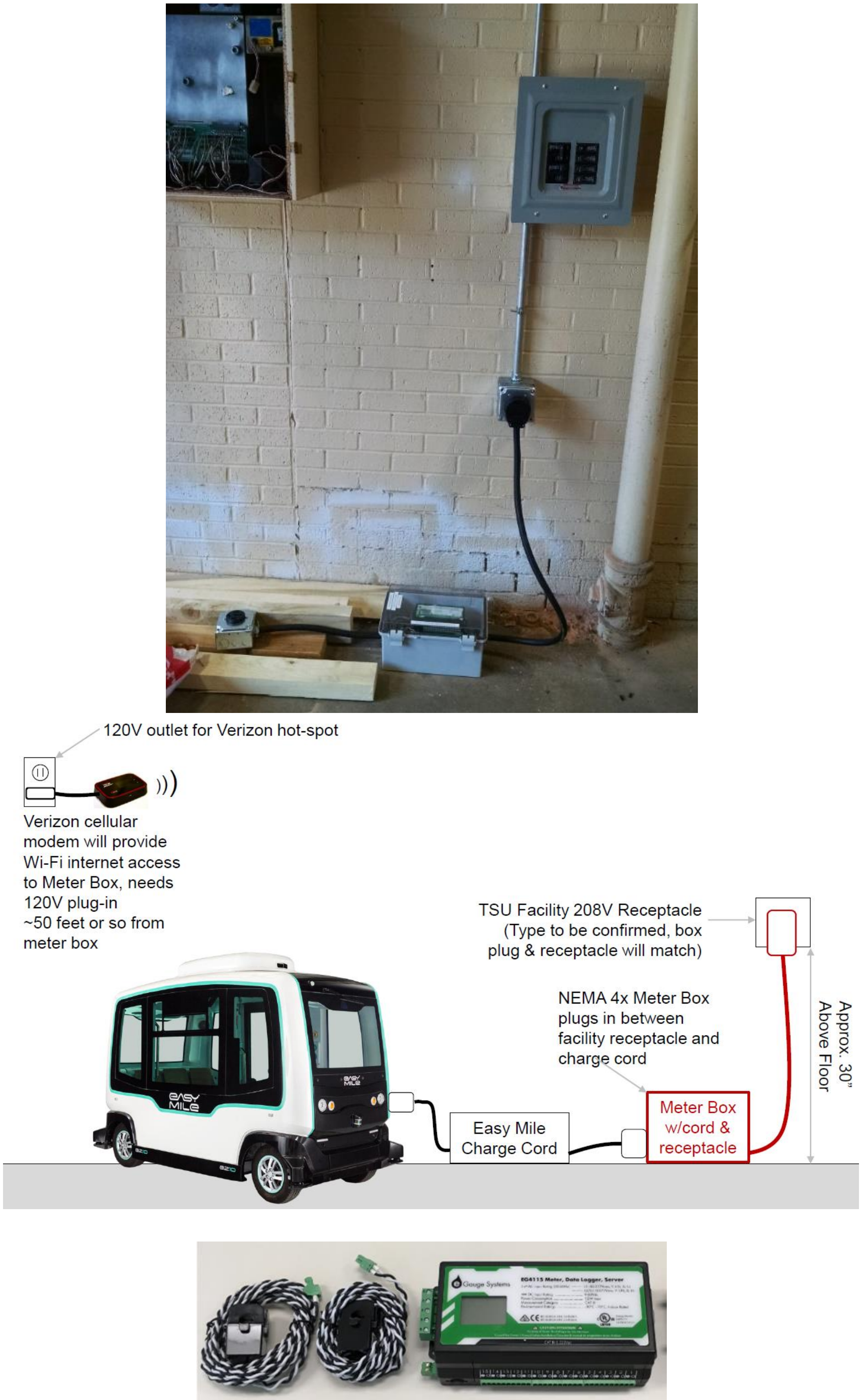


Figure 2-14 Configuration of INL Power Consumption Monitoring and Data Transmission Equipment

Source: Matthew Shirk, Idaho National Laboratory

Each day a log was kept of odometer readings in the vehicle before it was placed in passenger service on Tiger Walk, as well as the battery state-of-charge. This data logged, and then sent to INL for a periodic compilation of the power intensity energy consumption statistics. The daily power consumption data transmitted to INL by the data logger they installed in the maintenance and storage bay. In addition, INL investigated the ambient temperature of each day that records were available, in order to assess what impacts on energy consumption could be attributed to onboard air conditioning and/heating equipment used for the passenger compartment temperature control.

Table 2-1 shows the type of data records that were compiled for 89 days of TSU's AV Shuttle operation. INL was able to assemble a rich database of power consumption as a function of vehicle-miles travelled and ambient climatological conditions between June 10th and November 20th while the 2019 Phase 1 AV Shuttle operations were in active passenger service.

Table 2-1 Sample Data Compiled From Daily Operational Records and Energy Monitoring Equipment
Source: Matthew Shirk, Idaho National Laboratory

Vehicle ID	Operation Date	Distance Travelled (Miles)	Recharge Energy (AC kWh)	Energy Intensity (AC Wh/Mi)	Operating Time (hr)	Average Speed (mph)
TSU	6/10/2019	30.45	36.9	1212	9.27	3.29
TSU	6/11/2019	24.86	32.6	1312	8.38	2.96
TSU	6/12/2019	26.10	32.3	1238	8.45	3.09

Operations Data			
Date	Start SOC (%)	Start Odometer (km)	End Odometer (km)
10-Jun	100	300	349
11-Jun	100	349	389
12-Jun	100	389	431

Figure 2-15 illustrates the energy consumption as a function of the average vehicle speed. The primary metric derived from the compiled data is designated as an energy intensity value, with units of watt-hours per mile. The two boundary areas identified in the figure by dashed lines show the research conclusions for the range of energy consumption for both a lower speed AV shuttle (5 mph average speed[5]) and a higher speed AV shuttle (10 mph average speed[6]). These are important findings of the INL research concerning energy consumption forecasts for future AV transit applications, such as those discussed in

[5] The INL report to TSU expands on this hypothetical vehicle as having a fixed tractive-effort energy intensity requirement of 400 Wh/mi, a 5 mph moving average sped, and a time-constant power requirement ranging between 500 and 5,000 W while operating over a 25-mile route.

[6] The INL report to TSU expands on this hypothetical vehicle as having a fixed tractive-effort energy intensity requirement of 500 Wh/mi, a 10.67 mph moving average sped, and the same accessory constant load and route length as for the 5 mph hypothetical vehicle.

the next section for conceptual future Phase 2 route operations. Note that average operating speeds with all stop dwell times included for the Phase 1 TSU shuttle on the sampling of days shown in **Table 2-1** ranged from 3 to 3.3 mph, with the spread of data points shown in **Figure 1-15** being caused by the on-board accessory loads.

The data points are the compiled record of the average speed during a given day's operating hours (including time stopped in stations) and the distance the vehicle travelled. It is very significant that the energy consumption effects of seasonal weather on non-tractive loads -- primarily accessories like heating and air conditioning – proved to dominate the energy consumption for the low 3 to 4 miles-per-hour average speed of the Phase 1 operations within a pedestrian environment.

A conclusion of the INL research is that the lower the average speed of the AV shuttle vehicles, the more that Energy Intensity measures are driven primarily by the accessory loads of HVAC load for the cabin due to the many windows and large doors that open every time the vehicle stops to allow passengers to board and alight the vehicle.

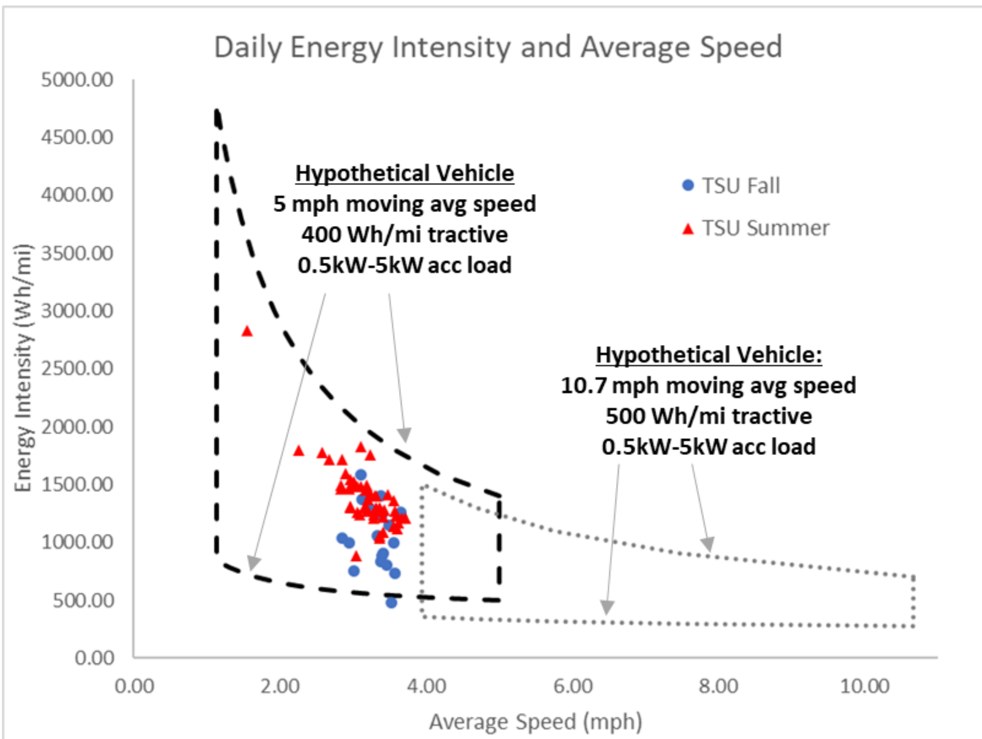


Figure 2-15 Energy Consumption Data as a Function of Average Speed and Seasonal Climate Impacts

Source: Matt Shirk, Idaho National Laboratory

The acronyms and nomenclature used in **Figure 2-15** are as follows:

- Daily vehicle average speed in miles-per-hour -- mph:
- Watt-hour per mile of vehicle propulsion tractive effort – Wh/mi. tractive
- kW acc. load – kilowatt energy consumed by accessory equipment loads (non-tractive)

The data was analyzed further for assessment of the impact of seasonal temperature variations, since heating or cooling by the vehicle air conditioning system was recognized as a primary factor when the vehicle's propulsion energy was relatively small when operating at such low speeds as occurred along the Tiger Walk. **Figure 2-16** presents the distribution of energy intensity values as a function of the number of days recording the scaled values shown.

Figure 2-17 illustrates the effect of the ambient temperature[7] on energy consumption observed for Phase 1 operations. These are indicative of the primary impact of the accessory equipment loads for climate control in the passenger compartment.

The information above was taken from the Idaho National Laboratory research that was presented by Matt Shirk in a February 18, 2020 meeting with the Houston project partners, with the permission of Mr. Shirk on behalf of INL.

One other aspect of the battery charge and the potential impact on operational hours before recharging was necessary was assessed during the Phase 1 operations. Specifically, the placement of USB ports inside the passenger compartment for the convenience and use by passengers resulted in frequent connections to mobile phones while students were riding the AV Shuttle. The Final Report includes a discussion of several test periods conducted in which multiple devices were charged, and anecdotal assessments of the vehicle battery life impacts.

[7] The INL report to TSU states that the hourly temperature data were retrieved from NOAA's Climate Data Online database for a weather station in the immediate vicinity of the TSU campus. The temperature readings between 8 a.m. and 8 p.m. were averaged as daytime daily averages.

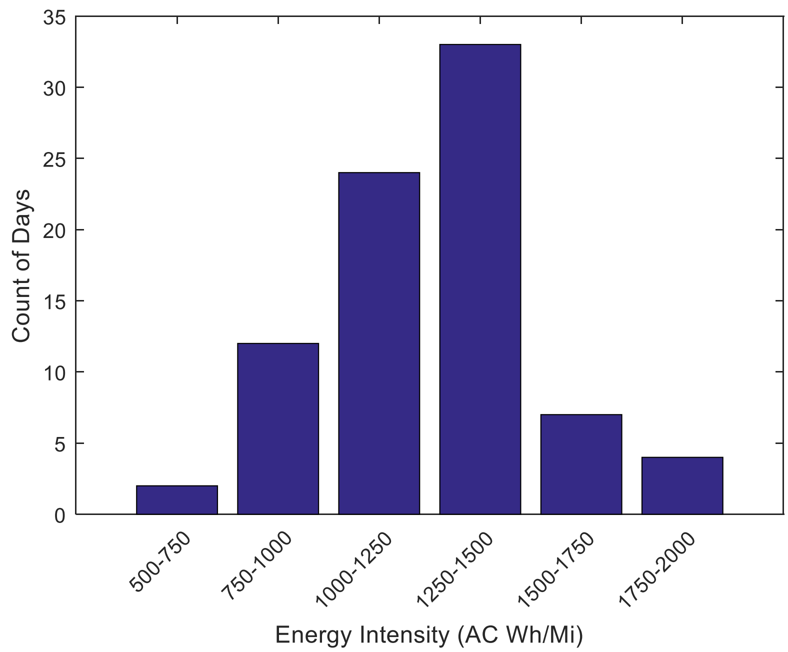


Figure 2-16 Histogram of Daily Energy Intensity from TSU EasyMile Phase 1 Demonstration Pilot

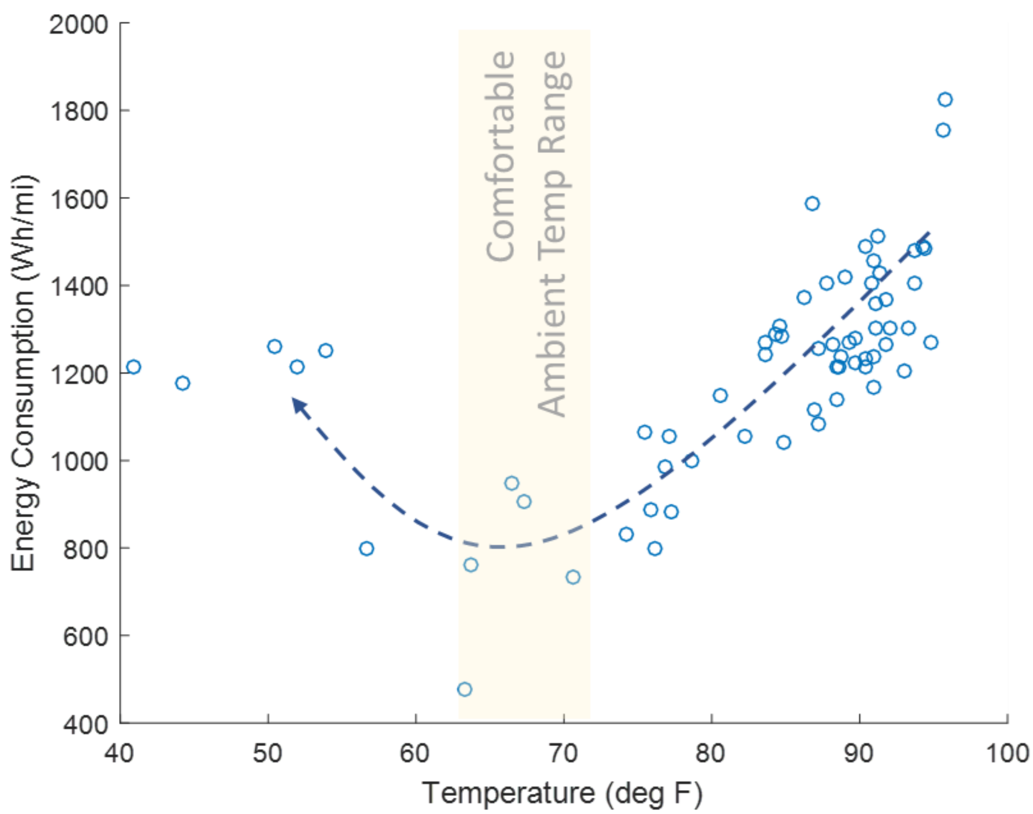


Figure 2-17 Phase 1 Energy vs. 8 a.m. – 8 p.m. Average Temperature

Section 3 Phase 2 Deployment – Regional High Capacity Transit AV Connector

3.1 Introduction to Phase 2 AV Connector Operational Planning and Cost Analyses

As an extension of this research study's research investigations and documentation of the actual Phase 1 deployment, the study also briefly considered the next planned phase of the University District AV Transit Circulator System. As of the date of this report, Phase 2 of the University District AV Transit deployment is under full planning and early pre-deployment preparations by Houston METRO and their Contractor, the First Transit/EasyMile team, along with the other entities involved in the University District partnership.

Phase 2 implements the extension of the AV Transit Circulator service off of the TSU campus to connect with Houston METRO's Purple Line LRT System at the western edge of the University of Houston campus. This critically important subsequent phase of development accomplishes an initial demonstration pilot of a first-mile/last-mile transit connector function by which a district is connected to regional high capacity transit. As it matures, this functional application of AV transit will induce a greater transit ridership overall for regional high capacity transit, particularly among peak period commuters who travel when the freeway and highway congestion is the most severe.

Phase 2 planning has been underway since 2019, and a preferred route alignment was established through consultation between Houston METRO, their Contractor team and the University District partners. **Figure 3-1** shows the preferred route that is being actively assessed by the project team, as of the date of this report.

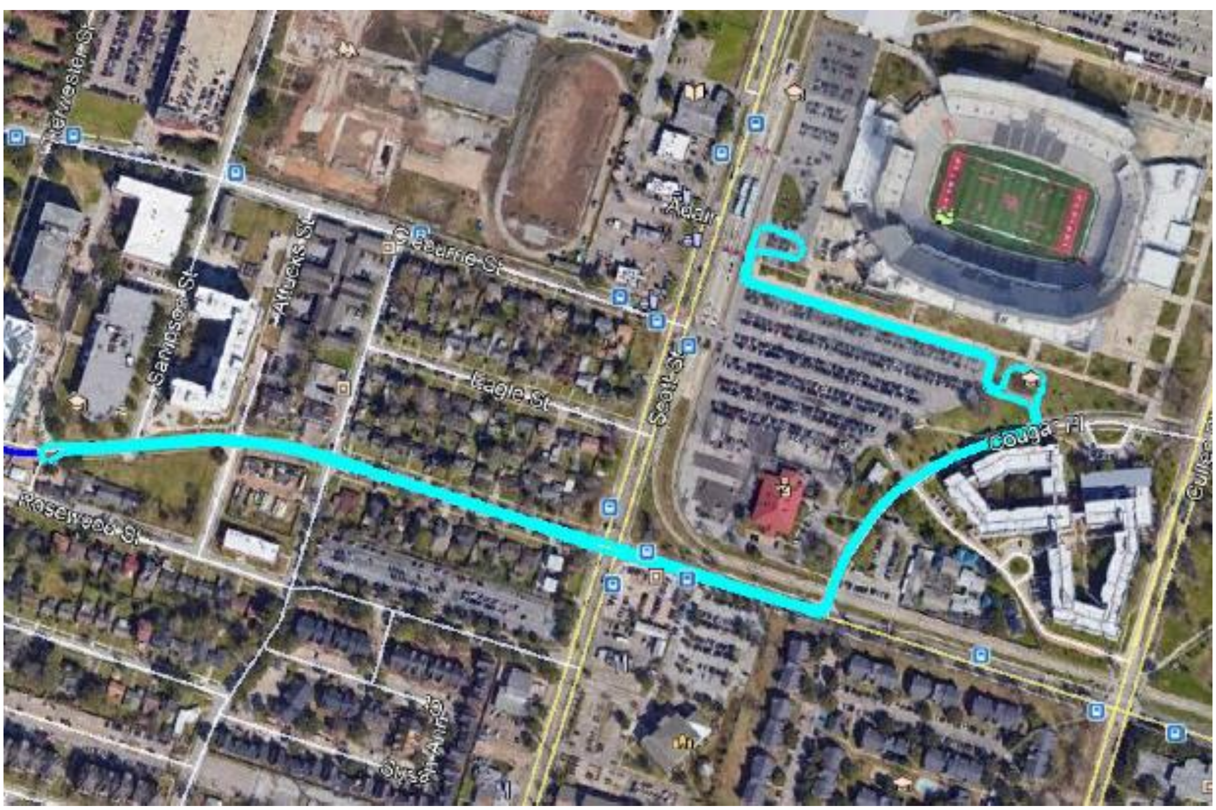
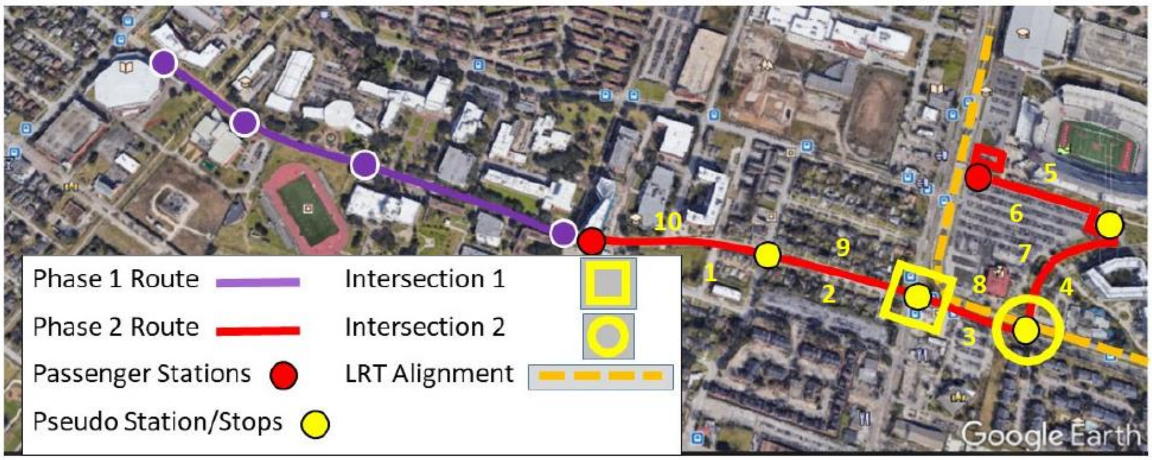


Figure 3-1 Preferred Route for the Phase 2 University District AV Transit Circulator System

Source: First Transit and EasyMile

The steps recommended by the Contractor team for the mitigation of safety risks have been defined for this preferred route, with particular attention having been paid to the two intersections shown in **Figure 3-2**. Intersection 1 is the signalized intersection of Wheeler Ave. and Scott Street, and Intersection 2 is the junction of Wheeler Ave. and Cougar Place where the crossing of the LRT line will occur. Intersection 2 currently has only crossing arm protection of the LRT tracks, but the safety assessment of the future Phase 2 deployment has recommended the addition of other traffic control features, such as stop signs on Wheeler Ave. and vehicle-to-infrastructure (V2I) communication links.



Operational Links Between Stations/Pseudo Stations

Link	Designation	Length (Ft.)
1	TSU Library Station to New Stop Sign at Attucks St.	975
2	Attucks St. Stop to Wheeler/Scott Intersection	740
3	Wheeler/Scott Intersection to Cougar Place Stop Sign	610
4	Cougar Place Stop Sign to TDECU Stadium Lot East Entry	975
5	Lot East Entry to TDECU Stadium Station at West End	745
6	TDECU Stadium Station to Parking Lot East Exit	1,345
7	Parking Lot E. Exit to Cougar Place Stop Sign/LRT Crossing	915
8	Cougar Pl Stop Sign/LRT Xing to Wheeler/Scott Intersection	615
9	Wheeler/Scott Intersection to Attucks Stop Sign	790
10	Attucks St. Stop Sign to TSU Library Station	870
	TOTAL ROUTE LENGTH IN FEET	8,580
	Total Route Length in Miles	1.63

Figure 3-2 University District AV Transit Circulator Preferred Phase 2 Alignment, Stopping Locations and Length of Operating Links

Figure 3-2 also shows the two passenger stations at the TSU and the U of H/LRT station end-of-line stations, as well as "pseudo station" stops which are used in the performance modeling that is explained as part of the analysis discussion that follows below.

Phase 2 Physical Planning – The lessons learned through the physical planning process of Phase 1 have allowed a more rapid determination of the essential planning elements for the Phase 2 deployment. At the time of this document's publication, the contractor has indicated that the vehicles available for deployment on the Phase 2 route will be EasyMile's EZ10 Gen3 vehicles. Although the new Gen3 vehicles are essentially the same size and performance level as the Gen2, there are a few important distinctions. Refer to **Exhibit A** for a comparison of the Gen2 and the Gen3 EasyMile vehicles.

One primary distinction between the Gen2 and Gen3 vehicles is that the newer model has an enhanced sensor set. The result of this improvement is that the sensory equipment has been concentrated at one end of the vehicle, creating a unidirectional vehicle that can only operate at its normal operating speeds going in a single direction along the route. For this reason, the vehicle must accomplish a reversal of its direction of travel through the route corridor with a 180 degree loop turn at each end of the route. This loop configuration can be clearly seen at each end of the Preferred Route Alignment in **Figure 3-1** above.

Figure 3-3 shows photographs of the two end-of-line stations for the Phase 2 Preferred Route. Each station stopping location allows convenient pedestrian access along existing pedestrian walkways. At the TSU library there is easy access from the campus Tiger Walk spine pedestrian corridor and at the from the LRT station – both of which can be seen in the background of the respective photographs.

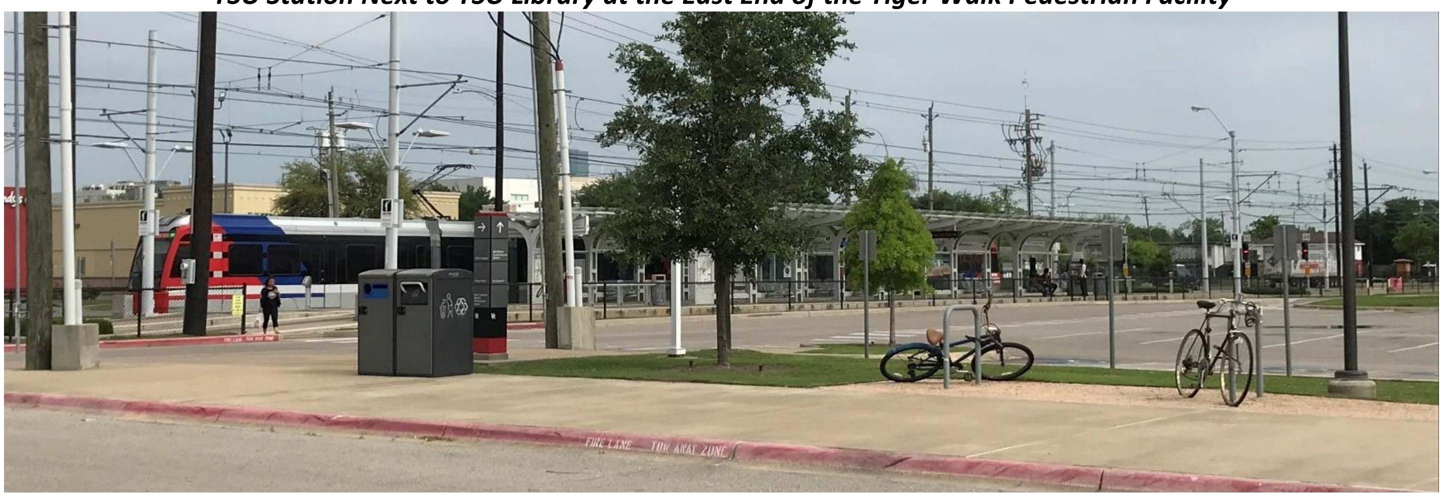
The proximity of the TSU station at the east end of Tiger Walk is strategically close to the existing storage bay being used for the Phase 1 AV Shuttle operations. The single AV Shuttle vehicle that operated since the summer of 2019 along Tiger Walk will continue to operate during the Phase 2 demonstration pilot. As noted above, the storage bay at the TSU Central Plant where the one EasyMile vehicle has been stored and where its battery can be charged is actually large enough to house the two additional vehicles that will be deployed on the Phase 2 route (see **Figure 2-13** above). Equally advantageous is the distance between be Central Plant vehicle storage bay and the east end of the Tiger Walk. This distance can be easily navigated under manual operation of the vehicle between the storage location and the Phase 2 end-of-line station at the TSU Library. Therefore, the same facility used throughout Phase 1 will continue to be used to store and to charge the vehicle batteries during the Phase 2 demonstration pilot project.

3.2 Overview of Analysis Process

This Appendix B documents an analytical framework of data and criteria by which a series of case studies are performed of future conditions represented by assumed levels of ridership. These ridership demand levels define in part the case studies for system operational performance analyses, and as well as the case studies of the estimated capital costs and operations and maintenance (O&M) costs.

The current METRO plan is to keep the single EasyMile Gen2 vehicle that has operated along the TSU Tiger Walk as a continuing fixed route shuttle for the on-campus transport service to TSU students, faculty and staff. This on-campus shuttle route will be referred to in the discussion that follows as the "Phase 1 Route". The Phase 2 connection that is added between the eastern end of the Tiger Walk and the LRT Station at the western edge of the University of Houston campus is being currently planned as a separate "Phase 2 Route" which is being evaluated for the operation of two additional EasyMile Gen3 vehicles. Initial operations of the Phase 2 Route will comprise a test program where the two vehicles will be operated along the route indicated in the figures above with only the Contractor employees onboard. Once passenger service begins, these attendants will remain onboard at all times that the vehicles are in automated operation along the Phase 2 route.

TSU Station Next to TSU Library at the East End of the Tiger Walk Pedestrian Facility



Purple Line Station at the Curbfront Adjacent to TDECU Stadium and Across a Driveway from the METRO LRT Station

Figure 3-3 Passenger Station Locations for the Preferred Phase 2 Route


© 2020 Google
Google Earth
1944
29°43'17.81" N 95°21'04.78" W elev 38 ft eye alt 198 ft

FIGURE 3- New

Therefore the "baseline vehicle the "baseline vehicle technology" has corresponding capacity, performance and operations parameters defined for us in the analysis process.

The methodology used to assessing the Phase 2 deployment is one that is called a "supply-side" analysis, in which the capacity of the system and the implications for its operation are evaluated for hypothetical demand conditions. This is considered a "systems engineering" approach in which a system design is tested for its ability to adequately perform when it is stressed under case study scenarios that could possibly occur, but which are not absolutely certain. This approach serves to support one of the primary purposes of this research project by providing insight into the future phases of the University District application of AV transit technology. But in addition to this one specific district application, these analyses also give insight into other potential applications of AV transit technology in diverse urban districts, campus environments and major activity centers – especially those which could be connected to high capacity transit services near their perimeter.

Vehicle Performance and Route Operations Analysis Variables – A planning level analysis of the Phase 2 operations has been undertaken in this TSU research project. This planning exercise not only provides insight into the immediate deployment of the Gen3 vehicles in the pending Phase 2 Demonstration Pilot, it also encompasses a "long view" looking forward to the time when fully automated and unmanned AV transit vehicles will be operating in mixed traffic on the Phase 2 Route.

The three variables that were analyzed for their effect on the vehicle/route operational performance along this preferred route were 1.) vehicle speed, 2.) vehicle capacity and 3.) ridership demand rates to be met. Each of the first two variables has a direct impact on the operating fleet required to provide the third variable's minimum levels of ridership carrying capacity.

These performance and operational metrics and the associated comparative case study evaluation criteria are discussed below.

Operating Speed – The current EasyMile Gen2 vehicles traveling along the Tiger Walk on TSU campus are programmed for a maximum "operating speed" of 8 mph. The new Gen3 vehicles that will operate along city streets and through U of H on-campus roadways will initially be programmed for 12 mph maximum operating speeds on the Phase 2 route. However, the EasyMile Gen3 vehicle is fully capable of operating at a operating speed of over 20 mph.

Therefore, the two sets of operating speed conditions that are analyzed in the case study definitions are:

- 12 mph
- 20 mph

Vehicle Capacity – Up to this point in time, the EasyMile vehicle parameters that have been advertised with respect to each vehicle's passenger-carrying capacity are based on six seated passengers plus six standing passengers, for a total capacity of 12 passengers.

However, NHTSA's is currently reviewing the operational safety for the EasyMile vehicles with regard to an incident causing a passenger's injury during an emergency stop braking condition, and this safety review has a direct bearing on the matter of vehicle capacity. In particular, this safety review by NHTSA[8] is indicating that they will disallow standing passengers during operation of the EasyMile vehicles from May 2020 forward. In consideration of the fact that the allowance of standing passengers may be withdrawn over the near term based on NHTSA's current concern for mitigating the associated risk of passenger injury, the minimum vehicle capacity of 6 passengers has been selected to represent this pending NHTSA directive.

In the future, however, with the anticipated improvements in the vehicle automation technology it remains possible for a more advanced version of the baseline vehicle to carry standing passengers, as well.

Therefore, the two vehicle capacity values that have been comparatively assessed in the analysis were as follows:

- 6 Passengers (all seated)
- 12 Passengers (both seated and standing)

Ridership Demand Rates – The configuration of the Phase 2 route is such that it will only provide a connection between the LRT Station and the east end of the TSU's Tiger Walk, as there are no other passenger stations along the route other than at those two locations. Therefore, the ridership on the Phase 2 route will only be TSU students and faculty, and it is reasonable to consider that the passengers will only alight (or board) the shuttle as transfers from/to a METRO train. Phase 2 ridership is not expected to comprise parking or drop-off passengers in light of the proximity of the TSU campus and the associated parking provided there.

Three ridership demand levels have been defined as a condition for which system throughput capacity can be assessed. All ridership demands discussed herein are expressed as TSU-bound campus access trips, although corresponding demand rates are reasonable to assume for egressing passengers leaving TSU and coming to the METRO station to board a train. The criteria for ridership demands is in terms of the assumed number of passengers that alight a METRO train within one headway – i.e., passengers from two trains, with one train arrival in each direction on the Purple Line during that time. The headways between trains on the Purple Line are 12 minutes, and the demand rates are assumed to occur multiple times during the peak morning hours as students and faculty are commuting to TSU via the LRT line, and connecting to the AV Shuttle.

The three sets of assumed demand rates that have been analyzed were established by the following number of passenger boardings of the Phase 2 AV Shuttle system at the METRO LRT station within any 12 minute period:

- 15 passengers
- 30 passengers
- 45 passengers

Case Studies Analyzed – The performance and operational analyses that was performed in accord with the Task Two scope involved various combinations of the parameters defined above. These parameters create reasonable conditions under which the Phase 2 system could operate over the near to medium

[8] As of the date of this report, the National Highway Traffic Safety Administration is actively reviewing the proposed mitigations that EasyMile has offered to address specific safety concerns raised by the agency. Elements of the mitigation plan include modifications to add seatbelts, audio announcements and procedural aspects.

term deployment of the EasyMile baseline vehicle technology. In all probability, the higher operating speeds, vehicle capacity and ridership values will not be reached over the next several years. But within a 5 to10 year period, it is reasonable to forecast that these conditions could occur, and the analysis is gauged to assess these prospective future operations[9].

The case studies shown in **Table 3-1** have been performed using the AV Shuttle performance and operations modeling tools. The shaded cells denote those case studies with the higher maximum operating speed of 20 mph.

Table 3-1 Case Studies of Phase 2 AV Shuttle Performance and Operations

Case Study Number	Vehicle Capacity	Max Operating Speed (mph)	Passengers During 12 Minute Peak Periods
#1	6	12	15
#2	12	12	15
#3	6	20	15
#4	12	20	15
#5	6	12	30
#6	12	12	30
#7	6	20	30
#8	12	20	30
#9	6	12	45
#10	12	12	45
#11	6	20	45
#12	12	20	45

It should be noted as a qualifying statement that none of these levels of ridership demand represent an actual ridership forecast. Rather, this analytical framework is what is typically called a "supply-side" analysis where the operating conditions and vehicle capacities are analyzed for hypothetical demands.

Although hypothetical, these ridership levels are plausible to occur at some point in the future when the entire University District AV Transit Circulator System has come to fruition. These demand levels could occur in future years when other parts of the University District AV Transit Circulator System have become operational – such as other AV transit service into the heart of the University of Houston or connecting to the Eastwood Transit Center. In these later phases, vehicles traveling from other parts of the District could connect into the Phase 2 route, or passengers arriving at the LRT Station on a different AV transit vehicle could transfer to this Phase 2 line.

Also relevant for purposes of this study under the auspices of H-GAC are the implications of increased ridership to defining minimum operating fleet size and passenger levels of service. This relevance is especially important with respect to assessments of the potential application of AV transit technology to other urban districts or major activity centers.

[9] It is noted that by the time the higher ridership demand rates are occurring, other extensions of this route beyond the LRT station, or other independent routes served by the same vehicle technology would in all likelihood also be in operation. However, only the Phase 2 Route was analyzed in order to retain a focused analysis.

3.3 Operational Route Modeling

The case studies were analyzed using a spreadsheet tool that has used in the past to model similar studies for Dubai, as well as for Mountain View, California. This modeling technique performed calculations for Phase 2 based on the route alignment shown in **Figure 3-3** above.

As shown in the figure, the number of passenger stations has 2 locations – one at the eastern edge of the TSU campus, and one at the west end of the TDECU Stadium curbfront, adjacent to the LRT Station. Also shown in the figure are the 8 "pseudo stations", which comprises 8 stopping locations along the route for essentially all AV transit vehicle-trips throughout the day.

The "pseudo station" designation shown in the figure indicates locations where the vehicle would commonly need to brake to a complete stop due to its movement within mixed traffic operations. In addition to those shown, a few other locations where the vehicle could briefly stop along the route were also accounted for through the delay values in the Performance Factors discussed below. However, the locations shown in the figure are much more significant in delay impacts, since they would typically require the vehicle to stop and wait for other vehicles (or infrastructure like traffic signals or train crossing guards) to clear its path before proceeding. In the case of the signalized intersection at Scott Street, the AV Shuttle would wait until the traffic signal changes to allow the vehicle to proceed.

The use of the analytical tools allowed the numerous case studies indicated in **Table 3-1** to be performed as comparative assessments of the variations in vehicle performance, operational fleet configuration, and passenger activity. Detailed summary tables were generated from each case study's input parameters. These tables, found in **Exhibit B,** show a more complete presentation of the operational performance and passenger service metrics that the case study models produced.

Performance Degradation Factors Considered in the Analysis – There are several adjustments that have been made to the performance parameters in order to estimate the operations of the vehicles within the mixed traffic, and in the maneuvering along the roadways, through parking area driveways and into station berths. The provisions for average stop/dwell delays at each of the pseudo stations and passenger stations therefore take into consideration this maneuvering through turns, through other traffic, and in the loop turn that is configured to allow the vehicle to reverse its direction at each end of the route alignment. When time trials were performed to assess these maneuvering impacts, it became clear that the travel time delay impacts were greater for the modeling of the 20 mph maximum operating speed case than for the 12 mph maximum operating speed case.

In reality, the benefits of the higher 20 mph operating speed for the Phase 2 alignment are less significant than first expected. This is true because the operating links between stopping locations are relatively short and the maneuvering trajectories along the circuitous route constrain the vehicle's operating speed over a significant part of the route, even though the vehicle is capable of operating at the higher speed.

Modeling of the AV transit vehicle's time and progress along the links of the route listed in **Figure 3-3** therefore included:

1. The time required to accelerate to the operating speed
2. The time to traverse the link, and
3. The time to brake to a stop at the end of the link.

4. Plus additional time delays due to localized alignment speed restrictions, as well as the impact of mixed traffic operations through intersections with traffic signals and stop signs.

The parameter described in number four above that was used in this technique to approximate vehicle performance degradation was an assigned value which estimated the average delay time at each station/stop location. And in particular for the higher speed cases, this delay factor also accounted for the speed degradation time delays while maneuvering through curves and turns along the link. The average station delay value also took into consideration the longer one minute dwell time that the vehicle would typically have at the two passenger stations. The following values were assigned for this time delay consideration as averages across all stopping locations:

- Avg. stop/delay = 28 sec. at 10 stations (passenger/pseudo) for Max. Operating Speed = 12 mph
- Avg. stop/delay = 40 sec. at 10 stations (passenger/pseudo) for Max. Operating Speed = 20 mph

As a result, the round trip time for the 12 mph vehicle performance level was approximated through model calculations to be 822 seconds (13.7 minutes), whereas the round trip time for the 20 mph vehicle performance level was 725 seconds (12.1 minutes). This comparison shows the effect of the required reduction in speed for the 20 mph performance capability, in particular while maneuvering along the portion of the route within the U of H campus.

<u>AV Transit Vehicle Speed Impacts on Other Vehicles</u> – There is another important but rather abstract impact that can be considered overall when assessing operational speeds. These are the factors which cannot be reflected in the performance numbers. Specifically, there is a significant effect of the AV Shuttle operations on other manually operated vehicles that are traveling behind and around the automated vehicle.

Experience around the world with early deployments of AV technology in mixed traffic has shown that driver frustration can be substantial when the vehicle is limited to a 12 mph maximum operating speed. This would be particularly important along Wheeler Avenue where operating speeds of other vehicles may be two or more times that of the shuttle. This fact alone makes the higher speed operations beneficial to consider as soon as the AV technology is ready to safely operate at the 20 mph operating speed. That fact is the basis for choosing the higher 20 mph speeds in some of the later cost analyses.

3.4 Performance Analyses Case Study Results

The results of the operational performance analysis for each case study produced several key metrics that are indicative of the cost to achieve the performance level desired, as well as the associated trade-offs of the level of passenger service that results from the operations. **Table 3-2** and **Table 3-3** show the key results for each of the twelve case studies that were analyzed.

The results are organized as **Table 3-2 Passenger Service-Productivity Parameters,** which provides an indication of how the combination of operational parameters within each case effect the ability of the system to move passengers quickly between their origin and destination stations. **Table 3-3 System Operational Performance Metrics** gives a different set of input parameters and analytical results as metrics which describe the system's operational performance in terms of quantifiable time and the maximum possible ridership throughput capacity. Note that some of the input parameters are listed in both tables. Also, the higher 20 mph speed cases are highlighted with blue shading to help the reader distinguish the values presented between the case studies.

Key Metrics for Passenger Service Productivity – Passenger service is a generally referred in terms of a "level-of-service" condition, and a "high" level-of-service typically denotes one of the most important objectives of public transit systems for the building of ridership. Conversely, if the level-of-service is low – such as when a passenger having to wait a long time until a transit vehicle can be boarded – then fewer potential transit patrons would choose to use the public transit system.

For that reason, the metrics representing level-of-service in **Table 3-2** are critically important to assess, and the performance and operational input parameters that impact the level-of-service metrics often become the most important variables to adjust. Of all the operational parameters effecting level-of-service, the one that is most easily adjusted is the size of the operating fleet.

Table 3-2 Passenger Service-Productivity Parameters

Case Study	Vehicle Capacity (Passengers)	Maximum Operating Speed (mph)	In-Service Operating Fleet (Veh.)	Peak 12 Min. Interval Throughput Cap. (Pass.)	Peak Interval Ridership Surge Flow (Pass.)	Avg. In-Station Service Waiting Time (Min.)	Typical Passenger Total Trip Time (Min.)
#1	6	12	3	16	15	2.28	9.13
#2	12	12	2	21	15	3.42	10.27
#3	6	20	3	18	15	2.01	8.06
#4	12	20	2	24	15	3.02	9.06
#5	6	12	6	32	30	1.14	7.99
#6	12	12	3	32	30	2.28	9.13
#7	6	20	5	30	30	3.65	9.69
#8	12	20	3	36	30	2.01	8.06
#9	6	12	9	47	45	0.76	7.61
#10	12	12	5	53	45	1.37	8.22
#11	6	20	8	48	45	0.76	6.80
#12	12	20	4	48	45	1.51	7.55

Table 3-3 System Operational Performance Metrics

Case Study	Vehicle Capacity (Passengers)	Maximum Operating Speed (mph)	Round Trip Time (Sec.)	In-Service Operating Fleet (Veh.)	Average Headway (Min.)	Route Hourly Throughput Capacity (pphpd)	Vehicle-Miles Travelled per Hour (veh.-mi./hr.)
#1	6	12	822	3	4.56	79	21.36
#2	12	12	822	2	6.85	105	14.24
#3	6	20	725	3	4.03	89	24.21
#4	12	20	725	2	6.04	119	13.14
#5	6	12	822	6	2.28	158	42.72
#6	12	12	822	3	4.56	158	21.36
#7	6	20	725	5	2.42	149	40.34
#8	12	20	725	3	4.03	179	24.21
#9	6	12	822	9	1.52	237	64.08
#10	12	12	822	5	2.74	263	35.60
#11	6	20	725	8	1.51	238	64.55
#12	12	20	725	4	3.02	238	32.28

The determination of the minimum fleet size value that was input to the model for each case study was made through an assessment of whether the operating fleet provides sufficient capacity to carry the case study's "peak interval demand". This "tuning" of the system operational fleet was done such that no passengers desiring to reach TSU within the peak demand interval would be left behind at the LRT Station due to system capacity deficiencies. On average, all case studies were set up such that AV Shuttle passengers would be able to reach campus within about 10 minutes. The minimum fleet is determined by a maintaining system passenger carrying capacity that was equal to or greater than the level of TSU-bound passengers that was delivered by the METRO LRT system during the peak interval. In effect, the fleet size variable was set such that there was an available transit vehicle arriving with sufficient capacity for every passenger to board within every twelve minutes (the LRT system directional headway)[10].

The three metrics that best depict this high level of service have the columns in **Table 3-2** accented by a double-line border that highlights these values. In particular, peak interval capacity provided by the operating fleet size is shown directly adjacent to the peak interval ridership demand value to illustrate that the fleet operations provided this minimum level of service for all passengers.

Key Metrics for Operational Performance – Operational performance metrics shown in **Table 3-3** describe how "productive" each case study is with respect to carrying a total quantity of passengers in each direction. This metric is typically defined as "passengers per hour per direction" (pphpd). The other common metric used in transit service assessments is the "headway" at which vehicles follow each other along the route. The metrics that effect these operational performance aspects were each assessed strictly with respect to the simple route configuration of the Phase 2 project.

The three metrics of fleet size, headway and route directional throughput capacity have their columns in **Table 3-3** accented by a double-line border highlighting these values

The analysis results most relevant to the early operations of the Phase 2 route are Case Studies #1 and #2, since the contractor team has developed the safety mitigation plan based on a 12 mph maximum operating speed.

In the summary section of this Technical Paper, the insight gained from these operational performance metrics and the associated overall analyses will be discussed with respect to its relevance to planning studies of AV transit technology applications in other districts and site deployments. The system's operational "throughput" capacity becomes the controlling factor in determining whether an overall system ridership demand can be met with a reasonable level-of-service. It is the key metric by which to assess how the AV technology's deployment as a small "automated transit vehicle" would work in other locations or types of districts, particularly at the point in the future when the technology can operate with fully automated, unmanned vehicles.

3.5 Selected Case Studies for Cost Evaluation

A selection of the case studies scenarios has been made for the Phase 2 route that are believed to be most likely to represent the near, medium and long term operational conditions for serving the basic first-

[10] Note that the current plan for initial Phase 2 operations will have two vehicles in service during the most active periods of TSU student access/egress travel during the day. However, the initial demonstration and testing period of Phase 2 is not expected to have demands at even the lowest levels included in this analysis. Therefore, the anticipated capacity limit of 6 seated passengers should be quite sufficient to meet the initial 2020 demand levels.

mile/last-mile function connecting TSU students, faculty and staff with reginal high capacity transit. The determination of the case studies for further cost analysis has been approached in light of the three most significant parameters described at the beginning of this section – those of vehicle capacity, operating speed and ridership demand level.

These parameters are most significant to future operations because they represent on one hand the challenges to be overcome as AV technology matures, as well as the corresponding opportunities to control costs. Conversely, they also provide an assessment of possible technology limitations which could thereby limit what AV transit can accomplish in the near to medium term, and as a result substantially inflate the associated project costs with larger fleet requirements as ridership demand levels rise.

Further to the discussion below, all scenarios assume that the system will provide "fully automated", Level 4 operations with vehicles running unmanned (i.e., approved for operation without an attendant onboard). This assumption also allows for an operations staffing level that provides continuous system monitoring through an appropriate operations control center. In addition, the staffing is assumed to include on-site operations personnel that are available for immediate response to go to and restore to operation any vehicle when it's automated driving system disengage for any reason, or to recover a failed vehicle to the storage facility.

The subset of case studies selected for both capital and L&M cost assessments are summarized below:

Near Term Scenario:

- Case Study #1 – 6 Pass. Capacity, 12 MPH Max Speed and 15 Pass./12 Min. Demand Rate

The Base Case is Case Study #1, which generally represents the AV transit vehicle technology capabilities at the current time. This is the most-certain scenario of a near term NHTSA approval for safe operations, with 6 passengers all seated and the maximum operating speed of 12 mph.

The demand level of 15 passengers in the peak interval of 12 minutes provides a minimum cost assumption for purposes of this analysis, and as shown in the case study summary table in **Exhibit B** this case would require a total fleet size of 4 vehicles. The fleet operating plan will have 3 vehicles in continuous service throughout most of the day, and 1 spare vehicle based on the practical criteria of a minimum 20% spare vehicles for maintenance and *battery charging considerations.*

Medium Term Scenario:

- Case Study #7 – 6 Pass. Capacity, 20 MPH Max Speed and 30 Pass./12 Min. Demand Rate

For the medium term of the next 3 to 5 years, the most important technology challenge that should be addressed is the vehicle's ability to safely operate at 20 mph maximum operating speed. This capability will address an important safety mitigation in that the traffic operating around the vehicle will not be substantially slowed and thereby will not induce frustration and "road rage" responses of drivers who are effected along Wheeler Ave.

The operating fleet size of this scenario is 5 vehicles, with a total of 6 vehicles required in the fleet.

Long Term Scenarios:

- Case Study #11 – 6 Pass. Capacity, 20 MPH Max Speed and 45 Pass./12 Min. Demand Rate
- Case Study #12 – 12 Pass. Capacity, 20 MPH Max Speed and 45 Pass./12 Min. Demand Rate

Over the medium to long term (5 to 10 years) as ridership increases by several times over what will be experienced in the near term, the advancement of AV transit vehicle technology capabilities should provide fully automated vehicle operations with speeds of 20 mph, which will in turn produce the advantages discussed above. Even if higher speeds are achievable by that time, the benefits to round trip time on the Phase 2 route will not be significant due to the alignment's inherent speed constraints, and the assumption of a 20 mph maximum speed therefore remains applicable for the long term.

But a more important parameter will be potential for increases in vehicle capacity if the approval is given for allowing standing passengers in the transit vehicle, even while operating at this higher speed. The pessimistic view would say that in mixed traffic, the only acceptably safe operating scenario would always be to limit the capacity to 6 seated passengers. But the optimistic view would allow for both 6 seated and 6 standing passengers, based on an expectation that automated driving technology will be so accurate, the vehicle design will be FMVSS compliant, and that emergency braking incidents will be so few in the long term that standing passengers can be transported along the route as or more safely as with human-operated vehicles today.

The operating fleet size of the Case #11 scenario is 8 vehicles with each limited to 6 seated passengers, for a total of 10 vehicles required in the total fleet with 20% spares. In contrast, the operating fleet of only 4 vehicles for the Case #12 scenario due to its 12 passenger vehicle capacity being twice that of Case #11, requiring a total fleet size of only 5 vehicles.

3.6 Evaluation of Capital Cost Estimates

It should first be noted that the key metric of fleet size is also the sensitive variable which most impacts capital and O&M cost in this simple estimation approach, particularly for the baseline vehicle used in the cost analysis – i.e., the EasyMile EZ10 technology. A second important assumption for purposes of the cost estimates is that the Phase 2 Route AV Shuttle deployment is a complete, fully automated transit system. The true threshold of major benefits will be realized when AV technology advances to the point where unmanned vehicle operations is the norm – a design capability that is expected in the near to medium term.

And third, the comparative capital costs for each case study are based on the inclusion of the supporting ITS/system equipment, maintenance facilities provisions, project engineering/management and project delivery aspects, which are referred to as "intangible project development" costs. To consider these as all "capital cost" could be viewed as procuring the project as a whole, rather than procuring just a fleet of AV transit vehicles. It compares to a procuring a complete operational project through a turnkey system supplier – a type of procurement that is common in the deployment of fully automated fixed guideway systems through a design-build, operate and maintain (DBOM) contract.

This last point is very important with respect to the interpretation of how these capital cost estimates of one case study may apply when there is an initial "system" procurement with a smaller operating fleet for the near term. Then over time the fleet would be progressively increased to reach a larger fleet as represented in the other medium and long term case studies. For this approach as a progressive procurement over time, it is reasonable to assume that the high initial system investment with ITS/system equipment, maintenance facility provisions and intangible project development would probably not be necessary as additional new costs over and above the cost of procuring only new vehicles to expand the operating fleet. This point is further discussed below as part of the capital cost comparisons between selected case studies.

Further discussion of the "capital cost" for a complete DBOM project will address how these costs should be viewed as "project costs" when there may be a number of the cost categories and subsystems that a transit agency/owner may be able to design and deploy with their own staff.

Definition of Capital Cost Categories and Subsystems – The cost development methodology used in the analyses described below has been used in a number of past projects to build up the costs for each "subsystem" or cost "category". The estimates have been based in part on the author's experience with the procurement of fully automated guideway transit systems. The subsystems have been adjusted to best estimate the comparable costs of automated vehicle technology as it matures to the level of a fully automated system.

The following list provides the general description of the component costs that were considered in the analysis. In some noted categories, there were no corresponding capital costs assigned for this Phase 2 project.

1. Transitway/Roadway
    a. NOTE: This category refers to civil works, for which no costs were included here for this analysis of the University District Phase 2 project. See also the comments in Footnote 11.
2. Vehicles
    a. Body and Equipment
    b. Onboard Control and Communications Equipment
    c. NOTE: There are additional cost components added to multiple other subsystems as a function of the number of vehicles.
3. ITS/System Automated Control Infrastructure
    a. Roadside Equipment
    b. Station Equipment
    c. Central Control Equipment
    d. Wiring
    e. NOTE: These costs are directly impacted by the number of vehicles and the number of stations.
4. Propulsion
    a. NOTE: No separate propulsion equipment costs (such as for fueling systems or overhead catenary wire systems) were included based on the assumption that almost all AV transit technologies would be battery-electric vehicles.
5. Communications
    a. CCTV / Security System Equipment
    b. Public Address Equipment
    c. Intercom Equipment
    d. Operations Radio/Telecom System
6. Battery Charging Power Supply
    a. Battery Charging Power Feeder/Substation
    b. Battery Charging System /UPS Equipment
    c. Grounding System
    d. Power Cabling/Circuit Protection

    e. Umbilical Connectors
7. Station Equipment
    a. AV Station Painting / Signage[11]
    b. Shelters and Station Furniture / Kiosks
    c. Fare Collection Equipment
    d. Station Lighting and Power Supplies
8. Maintenance Area Provisions
    a. Lifting and Handling Equipment
    b. Tools and Equipment
    c. Electronic Test Equipment
    d. Shop Furniture
    e. NOTE: The costs estimated for these maintenance area provisions did not cover the cost of the facilities in terms of construction or leasing, which is discussed further below.
9. Spare Parts and Supplies
    a. Spare Parts and Supplies
    b. Consumable Supplies
10. Intangible Project Support
    a. Project Management
    b. System Design Reviews
    c. Hazard Analysis
    d. O&M Manuals
    e. Contract Data Submittal Requirements
    f. System Testing and Commissioning
    g. Project Mobilization/Demobilization
    h. Bonds and Insurance
    i. Permits and Licenses
    j. Guarantees/Warrantees
    k. System Assurance and QC
    l. Operations & Maintenance Staff Training
    m. Special events to present the project to the community
    n. Meetings with other stakeholders such as police and safety officials, emergency services and first responders to inform them of specific aspects of the vehicle, AV technology, battery-electric propulsion and associated safety aspects, etc.

Design, build operate and maintain (DBOM) procurement is a common approach for acquiring a fully automated guideway transit system, and as such this type of procurement is usually considered a "capital cost". However, it can be seen from the list above that some of these costs could actually be covered by the transit agency/owner budgets for their own staff, equipment or facilities if the project is not a complete DBOM. In fact, some of the employee costs may actually be applied against an agency's operating budget and not strictly a capital budget. Therefore, the discussion that follows will refer to

[11] Note that the cost of these feature of painting and signage which were included for stations may also apply to the costs of roadway preparations in some AV transit deployments. An example would be the painting of the tiger footprints which already existed along the Tiger Walk on TSU campus (as can be seen in **Figure 2-2**) and which proved useful for AV localization purposes along the AV operating lane.

the estimates as "capital costs", with the understanding that they could be a combination of both capital and other budgetary "project" costs.

Capital Costs of Facilities – The cost of adding or expanding a maintenance and storage facility has not been included in the capital costs. Since the Phase 1 AV Shuttle operation has a facility currently provided by TSU which is capable of accommodating up to 4 vehicles inside the storage area, it is assumed that a similar arrangement would be provided in one or more of the existing campus buildings at TSU and/or U of H to accommodate larger vehicle fleets. The case studies with larger fleet sizes will require additional storage and charging facilities (and the associated power infrastructure), but capital costs associated with this additional facility capacity and associated costs are common expenses for transit agencies and are not included in this costs analysis.

Finally, the capital cost of building station structures has not been included, since the baseline technology is not designed with an intent for berthing at raised-platform station structures. Depending on the ultimate technology capabilities and depending on the future decisions to provide weather protection for the boarding area (or other such facilities costs), this assumption may or may not be correct. However, for purposes of this high-level capital cost assessment, station structures costs were not included, apart from a nominal allowance for painting and signage, station equipment, passenger shelters and related seating furniture.

Capital Cost of System Equipment – The cost of system equipment that is expected to be installed throughout the length of a fully automated system on the scale of the Phase 2 alignment has been included in this cost analysis. In this high level cost estimation for an defined system that does not extend beyond the basic alignment nor does it add additional stations, these types of costs would generally be about the same between all case studies, whether for a small 4 vehicle fleet or a larger 10 vehicle fleet.

For example the need for video security cameras and passenger intercom communications in station areas has a capital cost estimate based on the number of stations, and not the size of the operating fleet. In addition, the need for an operations control center where all vehicles are monitored and dispatched in real time, as well as vehicle/system monitoring equipment for the office where remote operations personnel would be based, would have capital costs that would be about the same for all case studies, whether for a 4 vehicle fleet or a 10 vehicle fleet.

Similarly, each passenger station location would incur the cost of roadway and curb painting to designate the station berth stopping point. In addition, each passenger station is assumed to require equipment installation for fare collection, boarding area lighting, passenger shelters and station furniture. These would be a one-time cost at each passenger station berth, even when other routes that may also stop at that passenger station location are added into the operation over time. Although additional costs would be incurred if new berths were added to the station locations over time, in all cases studies conducted for purposes of this report the headways were such that a single station berth would be adequate.

Finally, the system equipment costs necessary to install and supply communications radios among the operations personnel, as well as for installation of passenger communications intercoms in the stations, have been included. However, the extent of this equipment is not significantly different between the different fleet sizes in the case studies being considered here. Further, the V2I communications system connecting the operating AV transit vehicles with the roadway traffic signal system infrastructure (as well as the interfacing of equipment with the LRT signaling system) would be the same no matter how large the fleet size may be.

For the reasons discussed above, a similar value for capital cost was applied for most system elements that have the equipment required defined mostly by the route itself, not so much by how big or small the total fleet size was between the case studies that were compared.

Capital Cost Comparisons and Assessments – Capital cost estimates have been performed based on the premise that each case that was evaluated would be a complete new system procurement. The four case studies selected for capital cost comparisons (see discussion above) represent the procurement of a complete, fully automated transit system without consideration of an incremental increase of the fleet size from a smaller to a larger fleet (see discussion below). Based on this premise for a comparison of capital costs, a summary of the total capital cost estimates are shown in **Table 3-4**. A greater amount of detail on the related estimates capital cost by subsystem or cost category is shown for each of the four selected case studies in **Exhibit C**.

Table 3-4 shows the progressive increase of the complete system capital costs between first three selected case studies #1, #7 and #11, which ranges from $4.2M to $8.6 M. This progression of increasing costs also corresponds with the tripling of the overall system carrying capacity from 79 passengers per hour per direction (pphpd) to 238 pphpd.

It should also be noted that the case studies selected do represent the progression of higher capacities expected to be achievable over the longer term as technology advancements permit the increase of operating speed, while retaining the vehicle capacity of 6 passengers – a condition that would stipulate that all passengers would remain safely seated. This corresponds to the "pessimistic view" mentioned above which holds to the opinion that even over the long term (i.e. 5 to 10 years) AV transit technology will always require only seated passengers to be carried in the transit vehicle when operating in mixed traffic. This pessimistic view asserts that the only certain means to address operational safety concerns such as NHTSA is now considering is to prohibit standing passengers.

The forth case study in **Table 3-4**, however, shows the "optimistic view", which would assume over the long term that AV transit vehicles will be safe enough to allow standing passengers. As shown in the table, the doubling of the vehicle capacity in Case Study #12 reduces the fleet size to half that of Case Study #11, with a corresponding reduction of the system capital cost to $4.6M while matching the Case #11 throughput capacity of 238 pphpd.

Finally, the second column titled "Vehicle Fleet Capital Costs" provides a breakout of just the vehicle itself, including the onboard communications equipment. This is a component of the first column's value for the "Complete AV Transit System Capital Cost**".**

<u>Cost Impact of Subsequent Vehicle Fleet Expansion</u> – However, there are a number of other subsystems and supporting engineering costs comprising both hardware and software that must accounted for the complete system capital costs. This is important to consider when the initial procurement includes all of the system elements as part of the original implementation. Then, in a subsequent increase of only the vehicle fleet – while keeping the rest of the system the same – the additional capital/project costs account for only the additional vehicle influenced costs to be incurred – both the vehicle itself and the other system elements and intangible development where additional costs would be incurred.

Table 3-4 Capital/Project Cost Estimates for Selected Case Studies When Procured as a Whole System

Case Study	Complete AV Transit System Capital Cost	Vehicle Fleet Capital Cost	Total Fleet Size Incl. Spares (Veh.)	Maximum Operating Speed (mph)	Vehicle Capacity (passengers)	System/Route Throughput Capacity (pphpd)
#1	$4,158,072	$1,508,815	4	12	6	79
#7	$5,050,520	$2,263,222	6	20	6	149
#11	$6,835,417	$3,772,037	10	20	6	238
#12	$4,604,296	$1,886,019	5	20	12	238

As an example, consider the system procurement of Case Study #1 with a fleet of 4 vehicles and at a system cost of $4.2M. Then if at some point in the future 6 additional vehicles were added to achieve the higher passenger throughput capacity of Case Study #11, the additional cost for the expanded vehicle fleet would be in the order of $2.7M (the difference between the two Case Study total system capital costs).

This comparison is significant since it gives specific cost insight into the impacts of a subsequent fleet expansion after the initial system and fleet was already established and operating. The additional cost to add the two additional vehicles would be a total additional cost per vehicle of approximately $450,000 when the related system equipment costs, new vehicle deployment expenses and corresponding spare parts and supplies are included. This compares to the estimated values for the vehicle basic cost of $350,000 with an additional approximated cost of $35,000 for the onboard communications equipment.

In summary, "adding a vehicle" to the operating fleet costs more than just the basic "vehicle" cost. The total cost impact also include the other system equipment, spare parts and supplies and intangible project support, software and deployment/engineering costs, which are estimated to incur an additional $100,000 to the basic vehicle cost of $350,000.

3.7 Evaluation of Operations and Maintenance (O&M) Cost Estimates

The estimation of operations and maintenance costs for a fully automated AV transit system at this point in time can only be based on a combination of O&M cost experience from fully automated guideway transit, combined with a few examples of O&M costs incurred for demonstration pilot projects deploying AV technology. O&M costs for complete AV systems will only be fully understood after real projects are deployed over time as the AV transit industry matures.

Operation and Maintenance of a Fully Automated AV Transit System – The fact that a roadway vehicle based technology is operating along public roads with unmanned vehicles does not mean that there is no need for a substantive operations staff supporting the system operations.

What full automated does allow is for operations staff to manage and support a much larger fleet of smaller vehicles. In a sense, the bus operator who once drove a 40 passenger bus on a fixed route will in the future manage a much larger fleet of 10 to 20 passenger vehicles that are in service without the need any professional operator onboard. When fully automated, each vehicle can be automatically dispatched in real time to more efficiently serve the travel needs of individual transit patrons. Operations staff will be concentrated in an operations control center continuously monitoring the fleet operations, combined with a few strategically located field offices from which operations staff will respond by going to the vehicles if any problems occur.

Similarly, with the AV technology for transit applications evolving around primarily electric vehicles, the number of maintenance staff currently support a fleet of large 40 to 60 passenger fossil fuel powered buses will able to maintain a much larger fleet of small electric vehicles.

What this structure of support staff will mean for a system of fully automated, electric vehicles is that the cost to operate and maintain the larger fleet will be lower per transit user than conventional systems today. The structuring of service to include the demand-response mode of dispatching, combined with the smaller vehicle sizes in the fleet, will allow much of the peak period operating fleet to become dormant during the times of the day when demand falls, thereby allow an optimization of O&M costs per passenger served.

O&M Cost Categories – This O&M cost estimation approach has broken down the overall expenses into the basic categories of Payroll, Maintenance, Energy and Vehicle Fleet Depreciation. Already discussed above has been staff size implications with respect to the vehicle fleet and operating modes, with payroll aspects of the staff size directly affecting that cost component. Similarly, the maintenance costs for all-electric vehicles with only batteries and electric motors in the propulsion system will be relatively low, as has also been discussed above.

Depreciation of the vehicle fleet is an important aspect for the owner of the vehicle fleet – an entity that could be either the transit operating agency who owns the vehicles, the vehicle manufacturer who is leasing the vehicles to the owner, or a system contractor who is an independent design, build, operate and maintain business entity. After the initial capital cost to procure the system equipment, the cost to replace the vehicles as they age is typically considered to be an O&M cost for purposes of sustaining the operating fleet over a long period of time.

In general for purposes of this cost estimation, an "8 year" depreciation period was assumed based on other similar automated technology deployments that have been referenced. It is also important to note that the vehicle-mile accumulation over the 8 years will not necessarily be large in comparison to typical transit vehicles. However, the obsolescence of the vehicle technology overall is more important over the next decade since the evolution of the AV technology during the 8 year period will dictate the replacement of the vehicles by that time.

Finally, the energy costs are significant enough to warrant a separate cost category. For the battery-electric vehicle fleet the mode of battery charging will potentially be a cost factor, especially if many vehicles are charged at essentially the same time of day with high amperage "fast-charge" infrastructure. The cost implications due to electric-power demand charges will be a factor in the fast-charge approach, since power utility companies charge significantly more for high-demand energy consumption during peak periods of the day.

The transit industry will need to evaluate energy cost advantages for the alternative of using a "slow-charge" approach for vehicles while in storage during dormant periods throughout the day. Lastly, a "trickle-charge" approach with vehicle batteries being charged during their dwell time at each station could be the most cost effective with respect to energy costs.

Finally, the energy consumption implications of the data found through the Idaho National Laboratory research conducted during the University District AV Transit Phase 1 to the forecasting of energy use and the associated cost implications will be an important area of further research going forward (refer to **Section 2.5**, above). The climatic conditions, the design of the vehicle's HVAC auxiliary loads and the average operating speeds will eventually be part of the O&M cost estimation process, when those factors are better understood.

O&M Cost Comparisons and Assessments – The same selected case studies discussed above for Capital Cost comparisons have also been used for the development of O&M cost estimates. Annual O&M costs for these four cases range from $1.5M to $2.25M, with the results summarized in **Table 3-5**, and the details of the cost breakdown between the four costing categories are presented in **Exhibit D**. To assist in the comparisons between case studies, similar vehicle-fleet parameters are included in the O&M cost summary table as used in the Capital Cost Summary **Table 3-4** above, with the addition of the daily vehicle-miles traveled for the fleet.

Table 3-5 Operations and Maintenance Cost Estimates for Selected Case Studies

Case Study	AV Transit System Annual O&M Cost	Operations Staff Payroll Cost Component	Total Fleet Size Incl. Spares (Veh.)	Maximum Operating Speed (mph)	Vehicle Capacity (passengers)	Daily Accumulative Vehicle-Miles Traveled
#1	$1,563,860	$541,173	4	12	6	214
#7	$1,834,446	$811,760	6	20	6	403
#11	$2,240,326	$1,217,640	10	20	6	646
#12	$1,699,153	$676,467	5	20	12	323

Section 4 Summary Conclusions on District Scale AV Transit Deployments

The University District AV Transit Circulator System is planned over time to expand its service area from the initial Phase 1 and Phase 2 route to a service area that covers the three campuses, allowing AV transit circulation throughout the full district. At the future point in time when AV technology has fully matured, the Circulator System will provide a variety of transit services, both for internal circulation as well as first-mile/last-mile connections to regional high capacity transit – refer also in the introductory section's **Figures 1-1** and **Figure 1-2**, which depict the ultimate University District AV Transit plan. This future system will be totally automated, with vehicles operating without an attendant onboard. Dispatching of each vehicle's next trip assignment will occur in real time by an automated supervisory control system that is adjusting service to meet ridership demand patterns, and even dispatching vehicles in response to specific passenger service requests for travel directly from their origin to their destination stations.

The following discussion describes what is plausible to imagine as a diverse "transit system" of services involving an operating fleet of fully automated vehicles of a variety of sizes, all deployed to serve a variety of operating routes and modes of dispatching within a defined service area. For example, there could be an alternative scenario with a single operator providing the operational oversight and maintenance of all classes of vehicles within the University District AV Transit Circulator System – such as Houston METRO or their contractor. Equally conceivable is that there could be different contracted operators of multiple fleets (or different operating units within one agency), such as one fleet operator of fixed route services and another operator of demand-response services, all within the same district.

This view of a "district-level" scale of transit fleet operations fits well with the near to medium term capabilities for which automated vehicle developers are currently designing – deployments in "geofenced" areas with a high density of internal trips. The concepts described below not only describe what the University District AV Transit Circulator System is anticipated to become, they also describe how AV transit circulator systems in other major urban districts and major activity centers throughout the Houston region will develop, as well.

4.1 Physical Planning

As each new route and operating service is studied for near to medium term implementation, a district scale network of transit vehicle travel paths would first be established which interconnects the locations where significant numbers of trips originate and terminate. This investigation of trip-generation points serves to define the general proximity at which AV transit stations should be planned.

From the transit network and the associated analysis of trips that would be generated, combined with a quantification of the origin/destination (O/D) trip patterns and their dynamic changes throughout the day, those node pairs that have an exceptionally high "point-to-point" demand become strong candidates for the application of a larger AV transit vehicle and/or establishment of fixed route service between the prominent high ridership demand station pairs.

Other parts of the network that show a more uniform O/D trip pattern become candidate stations to be served by the demand-responsive form of service in which vehicles are dispatched by the supervisory control system in response to a demand call for a passenger trip between a specific origin and destination pairs. The layering of these service modes, route configurations and O/D station pairs would then be analyzed to determine the number of berths at each station that would be necessary to simultaneously board passengers during the peak passenger activity period of the day.

The following discussion addresses some of the physical planning aspects necessary for the expansion of not only the University District AV Transit Circulator System, but also the approach to AV Transit deployments in other new districts, campuses and major activity centers.

Vehicle Size and Performance Metrics – Current levels of vehicle performance and vehicle size in the University District early phases will continue to be "low speed", with maximum operating speeds up to potentially 20-25 mph. Operations within the Phase 1 Tiger Walk environment are constrained to about 8 mph due to the vehicle operating along a pedestrian facility.

Similar low speed AV shuttle deployments in other locations around the world which have some exposure to other traffic – such as along a dedicated lane within a city street – have been operating at between 12 -15 mph. However, these deployments have found that other conventional vehicles operating within the same space have the human drivers becoming frustrated with the slow speed, and the risks of incidents due to the low speed AV shuttle being overtaken by an impatient or inattentive human driver.

For that reason, vehicle speeds of AV technology operating in mixed traffic along arterial streets should have development and safety assessments focused on attaining speeds between 20 and 25 mph. Most AV Transit technologies designed for district circulation applications are being designed for this maximum speed range with respect to the automated driving system capabilities and the associated operational design domains.

Vehicle sizes ranging from 12 to 15 passengers (with both seated and standing passengers) are currently advertised by multiple sources, such as the EasyMile vehicle specifications describe 6 seated and 6 standing passengers(see **Exhibit A**) . However, the safety stipulations that NHTSA may impose for the immediate future restricting even low speed operations to seated passengers only add uncertainty at best to a near term allowance for standing passengers (refer to Footnote 11 above). It is therefore conceivable that increases in passenger capacity may only come through larger AV transit vehicles being offered in the marketplace.

Equally important with respect to the current NHTSA safety reviews is the fact that for the higher speeds necessary on arterial street operations, similar safety concerns could limit AV operations to only seated passengers in the mixed traffic environments. Additional guidance from NHTSA is expected in these higher speed deployments in the next year or so.

Larger vehicles are also in development, with a 24 passenger AV transit vehicle currently being deployed in a business district near Rotterdam. Full size buses are also now in development/testing. Further, small transit vehicles designed for 2 to 4 passengers are also in development around the world.

Over the next 10 years the many AV technology research and development initiatives will bring a variety of small, medium and large transit vehicle options to the market place. The ultimate scale and effectiveness of the University District AV Transit Circulator System may be accomplished using vehicle technologies that span a range of vehicle sizes, each applied to serve different parts of the campus roadway network and different portions of the ridership demand patterns.

Operating Mode and Route Configurations – The variables of operating mode and route configurations will be determined primarily by the continuing assessment and analysis of trip patterns and the relative demand levels throughout the district. Clearly, the scale and density of trips within the U of H main campus has the greatest concentration of internal district circulation trips. This will be conducive to a blend of AV transit service in the form of a network system serving on-demand dispatching of small to medium size vehicles and select fixed route services with larger vehicles. This would seem likely to be driven primarily by movements to and from the very large parking lots on the north side of the campus, and the two LRT stations on the south side of the campus.

The primarily east/west linear orientation of trip patterns serving the TSU campus, whether they be internal campus circulation trips or first-mile/last-mile trips connecting TSU students and faculty with the LRT high capacity transit stations at the edge of the U of H campus, will probably best be served by fixed route(s) or flex-route(s) service using medium-sized AV transit vehicles.

Extension of the AV transit service off campus to reach the Eastwood Transit Center, and potentially to ultimately to connect to the west to reach the Wheeler Intermodal Station, could significantly increase the ridership levels once the trip patterns and the regional transit mode share reaches its full potential. The corresponding first-mile/last-mile services may be best served by full-size AV buses – at least for the majority of regional transit patrons. The operating fleet sizes that can be practically managed and the times of day when ridership levels drop could provide opportunities for smaller vehicles operating on closer headways to serve these AV transit users who are connecting to high capacity transit during off-peak hours.

Operating Fleet Size and Service Levels – The main paradigm shift that AV transit technology will bring to operating fleets is the removal of a human operator from onboard every transit vehicle. When one operator that used to drive a single large transit bus can be supporting the operation of 10 to 20 smaller AV transit vehicles, then the customer level-of-service that can be provided has the promise of dramatically improving. Dynamic dispatching to provide optimization of transit service as ridership demand patterns fluctuate (e.g., high demand peaks concentrated during class change periods) will be managed in real time by the automated supervisory control system. This computer-based management system will allow operations personnel to focus on passenger service matters (such as an disabled passenger assistance), vehicle operational issues (such as a unauthorized vehicle blocking a station berth), and occasional automated vehicle failures requiring a human to intervene after the vehicle brings itself safely to a stop.

Using automation to continuously optimize the fleet operations, sending vehicles to a suitable storage location when demand levels drop or when a vehicle's batteries need to be charged, will be completely managed by the supervisory control system. The benefit will be not only the optimization of fleet operations with respect to the achieving the lowest practical vehicle-miles traveled and the corresponding energy consumption, it will also allow optimization of passenger service when smaller vehicles are accessible with much shorter waiting times. In fact, one of the concepts for on-demand services is to stage dormant vehicles in the station berths during low activity periods such that a passenger arriving at the station would be able to immediately board a ready vehicle, which would then be dispatched to the passenger's destination without any delay.

This transit operations paradigm shift will create transit fleets with a mix of vehicle sizes, and generally with smaller vehicles overall. In order to assess the combination of operating routes and modes, vehicle sizes, battery charging sequences and passenger service levels, the complexity of the operations will require analytical tools that simulate these diverse operations and allow sensitivity analyses of the many variables.

Vehicle Storage and Battery Charging Accommodations – One of the key aspects of automated, on-demand services is that strategically located vehicle storage facilities become an important part of the system design, especially when the ridership level has large fluctuations throughout the day. During times of the day when a significant part of the vehicle fleet is dormant as their operation is unnecessary to meet demand, then having storage facilities located to hold vehicle close to the next source of peak demand becomes very important. For example, a storage area close to the parking lots would allow a number of vehicles to be staged there to carry the morning surge flows as students arrive for classes.

The creation of storage locations also allows battery charging infrastructure to be places where it is most useful, strategically located throughout the operating network. When a vehicle can dwell in the storage area for 15 of 20 minutes every other hour, the duration of its service time can be greatly extended before it has to be taken out of service for a more extended battery charging period.

4.2 Route Operations and Project Costs

Operational Performance – Analysis of vehicle performance between station pairs for demand response service, as well as vehicle performance studies of a transit vehicle completing a round trip for fixed route operations, forms the initial step in the operational assessment of one or move overlay routes and service modes. For a simpler fixed route, the performance is a function of the maximum allowable operating speed (which may vary along different links) as well as the travel delays imposed from operating in mixed traffic with the associated movement through signalized intersections and stop signs along the route.

As the operating conditions of mixed traffic along more congested roadways is necessary to address in the physical planning phase of study, the use of simulation tools will become necessary. This need to apply computer modeling and simulations becomes even more important when studying the operational performance of on-demand service within a roadway network, providing customized transit services that has non-stop travel between a passenger's origin and destination stations.

Level of Passenger Service – Analysis of passenger service levels through quantification of waiting time at the origin station and travel time onboard the vehicle typically is also best addressed using modeling and simulation tools. The testing of different station locations, operating modes, and fleet size would be applied as variables to the analytical study, with the modeling results producing passenger service levels. Levels of customized service for different portions of the ridership within the district, as well vehicle size and alternative shared-ride scenarios would thereby be able to be assessed.

From the number of stations and the associated number of boarding/alighting berths required throughout the district network, combined with the operating fleet size that is necessary to meet the passenger service level criteria set for the AV Transit System, the analysis would then be used to establish the key parameters that drive capital/project costs, as well as operating and maintenance costs.

Capital/Project Costs and O&M Costs – Lastly, the alternative locations and the associated size of the operations, storage and maintenance facility(ies) that would be required to support a fully automated AV transit operations would be addressed, once the other analytically defined parameters and operational performance metrics have been established. In addition, the battery charging requirements for sustaining the operating fleet throughout the day – based on the ridership demand levels and trip patterns to be served – would be analyzed in terms of battery charge levels and hours of operation for the fleet. These data would allow a more refined assessment of the total AV Transit fleet size that would be required

All of these factors are the primary drivers of the capital/project costs and the operations and maintenance (O&M) costs. Time will give a better basis of the probable capital and O&M costs to be anticipated as actually AV Transit system deployments begin to be procured in increasing numbers of deployments.

4.3 A Microcosm of the Future of AV Transit

The University District AV Transit Circulation System will have a substantive effect on how public transit is understood and utilized within the Houston region. **Figure 4-1** illustrates how this functional application of AV "microtransit" using relatively small transit vehicles like the EasyMile EZ10 vehicles will work to provide internal circulation within urban districts and major activity centers. And more importantly, the functional application of this same AV Transit technology will be very effective in providing first-mile/last-mile services which connect the heart of the district with regional transit at intermodal stations, as represented by the University District Phase 2 deployment.

This illustration shown in the figure was developed by H-GAC staff in concert with the TSU Center for Transportation Training and Research work in support of the H-GAC High Capacity Task Force in 2018 and 2019[12]. The vision of Houston that is introduced by the work of this Task Force will dramatically change the way we view public transit. The transit system of the future will be an integrated, multimodal system utilizing automation to ultimately lower costs and energy use while dramatically improving the level service provided to every transit patron.

The University District's initiatives through the Phase 1 and Phase 2 deployments are the first steps along this road to Houston's very different and exciting transportation future. The insight gained from the Phase 1 physical planning studies and the corresponding operational lessons learned, when combined with the Phase 2 operational performance analyses contained in this document, support a better understanding of future AV transit technology applications in other districts and site deployments.

The system's operational "throughput" capacity on each route and within each station becomes the controlling factor in determining whether an overall system ridership demand can be served with a reasonable level-of-service. It is the key metric by which to assess how AV technology's deployment as fleets of small, automated "micro-transit" vehicles will work in other locations or types of districts like the University District.

And as travel demand studies begin to incorporate these level-of-service benefits and their impacts on transit mode choice, the corresponding site planning studies will be ready to also assess the cost effectiveness of deploying AV transit technology which can operate as a fully automated, unmanned vehicle system.

And so the vision that the University District AV Transit Circulator System embodies a microcosm of the future of transit service that will become realty throughout Houston during this century. As has been imagined in **Figure 4-1**, and as will be demonstrated through the coming phases of the University District transit deployment, AV transit circulation systems will create a wholly new type of mobility within urban districts, university and medical campuses and major activity centers. In addition, regional higher speed

[12] The summary report of the High Capacity Transit Task Force can be accessed through the web link given below. Note that the illustration was prepared by H-GAC and can be found in Appendix A of the Summary Report. http://www.h-gac.com/high-capacity-transit-task-force/high-capacity-transit-summary-report.aspx

AV buses will move passengers quickly through the protected HOV lane system that reaches to the edges of the Houston Metropolitan Area.

This is a major part of the solution for the massive congestion the region faces by mid-century. An integrated and highly efficient multimodal transit system will provide frequent service with customized travel to meet the mobility needs of the general public. Through these benefits of automated transit systems, the choice of transit as the mode to travel throughout Houston will drive the growth of ridership on public transit to higher levels than are possible now. The University District vision of AV Transit technology integrated with regional high capacity transit service truly is a microcosm of what will become reality over the next few decades in districts throughout the Houston region.

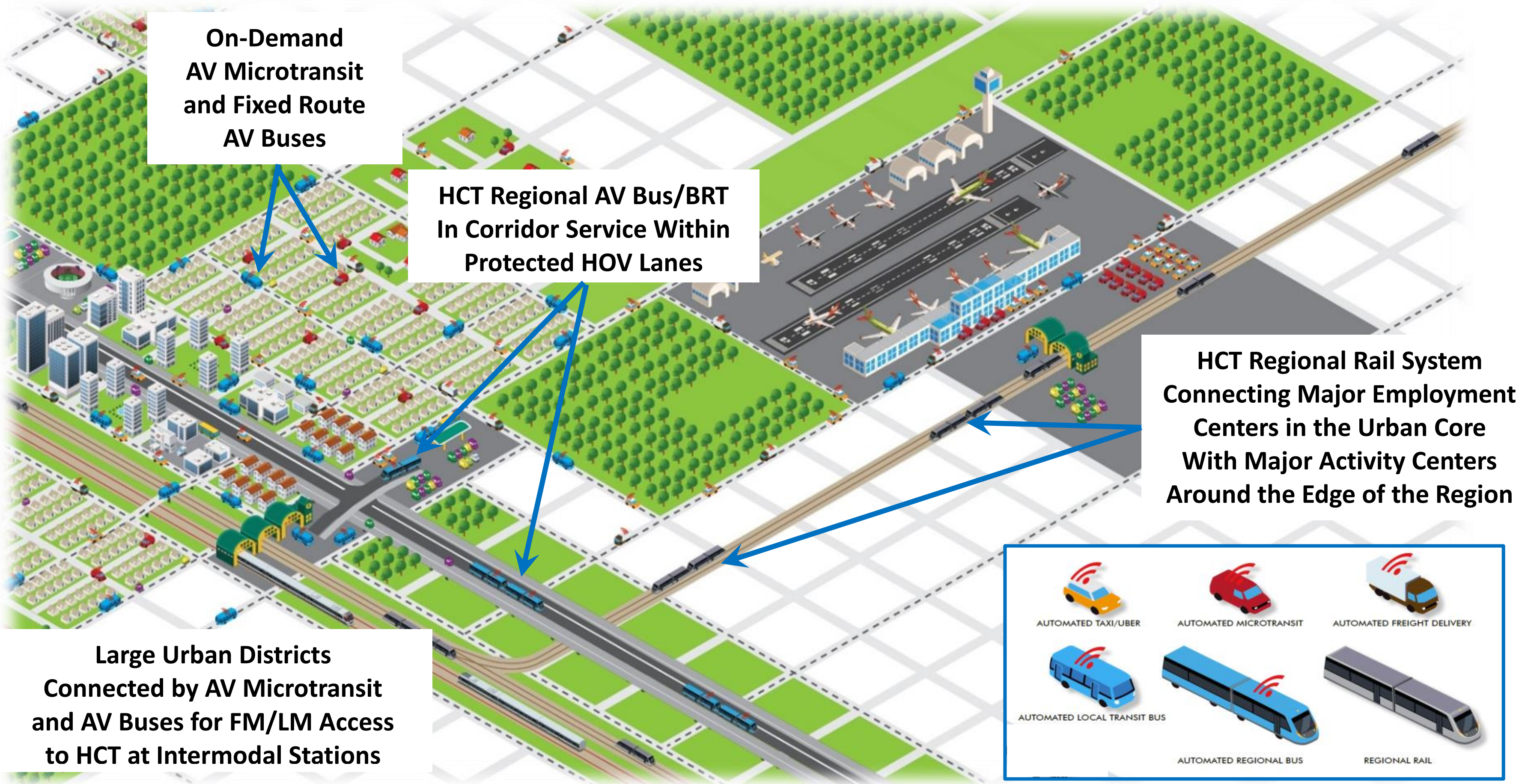
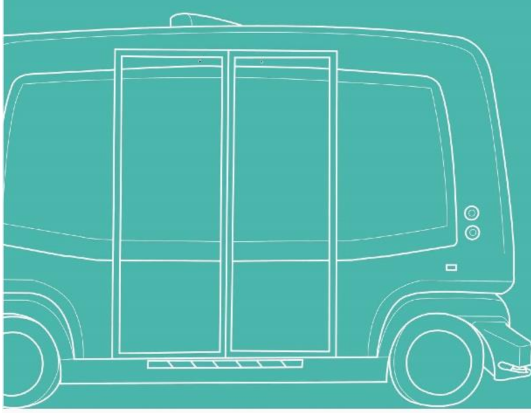


Figure 4-1 Multimodal Subregional and Regional High Capacity Transit Services All Connect at Major Business District Intermodal Stations

Source: Houston-Galveston Area Council

Exhibit A EasyMile EZ10 Gen2 Vehicle and Gen3 Vehicle Specifications

The information provide in this Exhibit has been provided by EasyMIle, and it is being used in this Report with their permission for Public Release.



EasyMile EZ10 Generation 2 Specifications

Reference | EM-EZ10Gen2-SPC-Light-EN
Date | January 18, 2019

Table of Contents

Introduction

Scope

The purpose of this document is to synthesize the general technical characteristics of the EZ10 Generation 2 vehicle, designed to be integrated as a component in an Automated Road Transport System (ARTS).

Status

This document provides a snapshot of the work progress on its completion date. The technical elements presented in this document are likely to evolve during the ongoing design process.

Technical Characteristics

Overview of the EZ10 Vehicle

EasyMile's EZ10 is an electric collective transportation vehicle, able to carry up to 12 passengers. It is fully electric and embeds automated driving capabilities, designed to be integrated in an Automated Road Transport System (ARTS) – a specific Automated Mobile System (AMS) dedicated to public transportation – in private areas or cities.

As an essential component of a global ARTS, the EZ10 aims at offering public transport system services based on the use of automated road vehicles, including scheduled, on-demand or door-to-door services on a specific pre-designed road network.

The EZ10 being fully flexible, the global transport system is highly adaptable. The pictures below present two different modes of operation that can be followed by the vehicles.

On-demand vs. scheduled services

The technical characteristics of the EZ10 are detailed below.

Description of the EZ10 Operation

The **EZ10** can operate in two driving modes:

- **The automated mode** is the normal operation mode of the EZ10. In this mode, the vehicle is self-driven and follows its programs and missions.
- **In manual mode,** an Operator drives the EZ10 manually with a specific remote control unit. This is not its standard operation mode. For instance, the manual mode is used when the vehicle is not fully operational, when the operator needs to drive outside its circuit or for any other necessary intervention.

Characteristics of the EZ10 Gen2

Operational Characteristics

Item	Description
Description	Public transportation system for "last kilometer applications"
Trademark	EasyMile EZ10 Gen2
Type of vehicle	Electric automated shuttle
Vehicle driving automation	Level 4 – High Automation (According to SAE J3016)
Passenger capacity per vehicle	Up to 12 passengers depending on conditions
Seated / Standing	Up to 6 seated / 6 standing
Driving modes	Automated mode (normal mode) Manual driving mode with on-board remote controller (exclusively reserved to Operator use)
Driving directions	Both directions equally, vehicle is front/rear symmetrical
Supervisory Control System	Available with EasyMile Fleet Manager solution
Track Length	Last mile applications, typically < 5km
Number of Stations	Typically 1 station every 200 - 400m [1]

Accessibility and Comfort

Item	Description
Access Door	Automated full frame double door Key locking system Sensitive edges Internal/External emergency unlock system
Openings	1 large window
Passengers Comfort	6 seats 2 stand-up seats
User Interfaces	29" information internal screen Interactive tablet with stop request functions Door open/close button Ramp up/down button Intercom button Emergency stop buttons Audio & visual warning alarms Audio/Video Intercom with supervision
Air Conditioning	Rooftop Air Conditioning unit Heating also available

Technical Characteristics

Item	Description
Chassis & Frame	Aluminium & Steel
Body	Composite – Polyester resin reinforced with fiberglass Internal and external shells made of non-flammable materials
Windshield & Windows	Windshield: Laminated glass, heated Windows: Tempered glass
Net Vehicle Weight	2,050 kg (4 battery packs & enhanced A/C)
Max. Load Capacity	1,000 kg (1.10 US t)
Gross Vehicle Weight	3,050 kg

(GVW)	
Length	4,020 mm
Width	1,998 mm
Height	2,871 mm with A/C 2,567 mm without A/C with suspensions lowered
Minimum Turning Radius	5 m (measured in the middle plane of the vehicle) 6 m (measured wheel to wheel, external)
Energy	Electric
Battery type	Lithium Iron Phosphate (LiFePo4)
Battery Management System	Yes
Charger	Wired / On-board
Charging time	Typically 6 hours
Traction	2 x independent asynchronous electric motors
Transmission	4 wheel drive
Direction	4 steering wheels (electrical actuators)
Max. speed	EasyMile operating max speed is currently limited to 20 km/h. The powertrain allows a maximum speed of 40 km/h.
Max. slope	8% nominal, up to 12% @ GVW for limited time
Service brake	Redundant electrical (regenerative) and hydraulic (on discs) brakes
Parking brake	Electrical calipers (one per wheel)
Emergency brake	Fail-safe brake
Suspension	Independent / Type Mc Pherson
Shock absorber	Variable height pneumatic damper Automatic height adjustment
Wheel rims	15 inch steel, optional aluminum rims

Tires	195/70 R15
Lights	Projectors, indicators, daytime running light, stop lights, retro-reflectors. Lights are symmetrical front/rear All light modules have EC automotive approval
Connectivity	Wireless RCU (UHF) for manual driving GSM / EDGE / UMTS / LTE modem Wi-Fi modem V2X module (optional)

Embedded Technologies

Item	Description
Components for Localization	Hybrid localization technology combining odometry, IMU, LIDAR, GPS
Components for safety functions	Detection LiDARs and cameras Safety relays, emergency stop switches, Audio & visual warning alarm
Communication Features	Permanent 3G or 4G connection to EasyMile cloud infrastructure Vehicle to Infrastructure communication
Passenger information system	Passengers interface can be customized with local or distant web pages displaying passenger information or commercial messages.

****

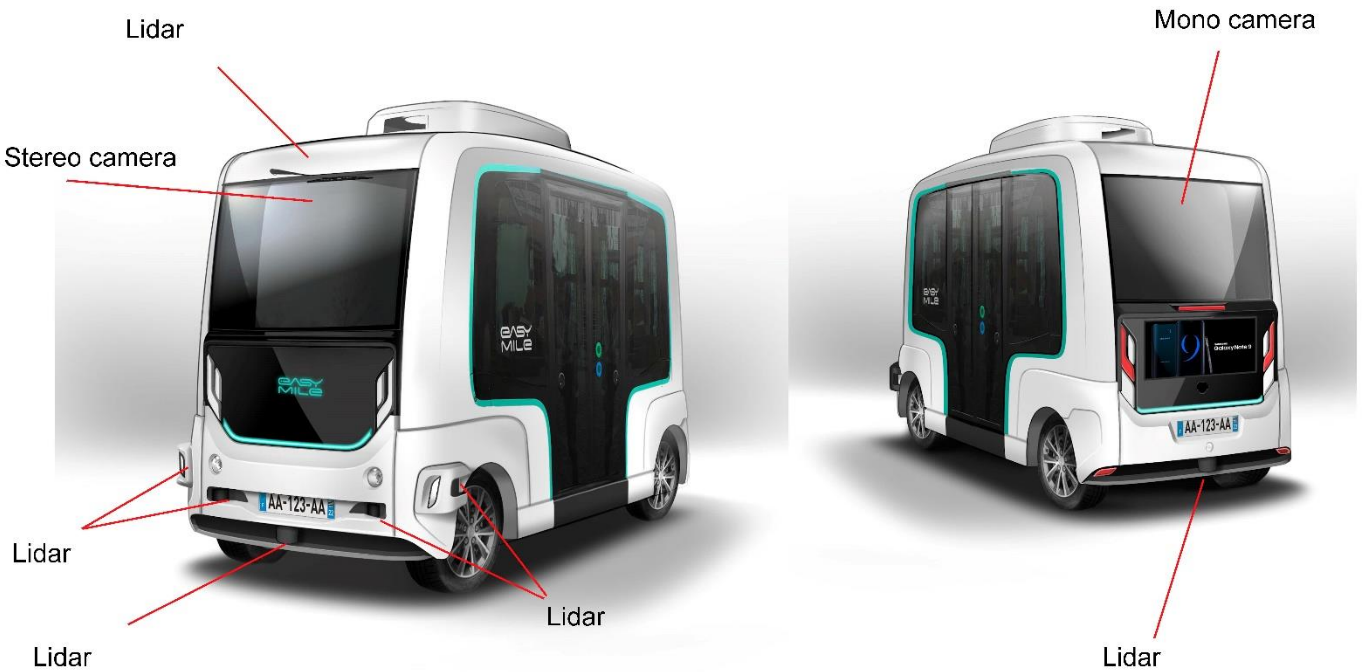
Introduction to EZ10 Gen 3

Gen 3: An evolutive platform with richer potentialities

The EZ10 Gen-3 is a platform that will allow:

See farther and better to **drive faster**, drive under **bad weather** conditions, and cross more type of **intersections** without human validation	New sensor set
Better interpret the environment to have more specific reactions, **increase average speed**	More computing power and especially new "vision" computer, redesigned Redundant Collision Avoider
Make our shuttle a **better support for public relationship** / brand support and improve passengers comfort	Improved outside design, new set of options for the inside

New design, monodirectional, and new sensor set



A richer sensor set, to see better and further

Gen 2	Gen 3	Rationale
LIDAR - 16 layers 80cm above the ground	LIDAR - 32 layers On the roof	• Better density for **detection and tracking** , especially at long distance (better anticipation) • Better positioned to "protect" the Redundant Collision Avoider, and larger vision angle
2 multi layer LIDARS		• Used for **localization** in Gen 2, replaced by 32 layer LIDAR in Gen 3
Single layer LIDARs 30 cm above the ground	Multi layer LIDARs 20 cm above the ground	• 4 layers instead of 1, better filtering of dust, leafs, … • key inputs for **Redundant Collision Avoider** • Redundancy to 32 layer LIDAR for short distances
Mono B/W camera	Stereo color camera	• High density, better perception of unconventional vehicles

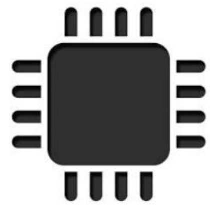
What's new?

Zoom: adding the vision to our shuttle

Sensors

Stereo camera
- better perception of unconventional vehicles (forklifts)
- High density

Vision PC



- More computing power, with powerful GPU, dedicated to manage signals from stereo camera

The stereo camera paves the way for features under development: deep learning, object tagging and tracking, especially for intersections
→ The EZ10 Gen-3 will be able to have higher average speed, better driving comfort, less false positive. These improvements will be visible in operations in 2021.

Main platform evolutions - Options

		Description
Comfort	New heating system	Floor warming + redesigned air flows
	Fabric seats with / without belts	More comfortable / less cold / seatbelts & neck-cushion
Energy	Battery	New battery pack autonomy +30%
Navigation	Mono directional	Normal driving in one direction only. The EZ10 can still go backward on short distances, for parking for example
Options available	Accessibility	WheelChair Anchor point, new access ramp
	External display	Displaying line name
	Automatic Passenger Counter	Connected to EasyMile Monitoring API
	Customer logo retro-lighted	Rear logo customizable with client's own logo

Seats

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Exhibit B Performance and Operations Modeling Case Study Summary Tables

Exhibit B Performance and Operations Modeling Case Study Summary Tables

Case Studies #1 and #2

CASE STUDY DESCRIPTION	Plng. Criteria Classification	System Parameters and Characteristics			
Case Study #1 **6 Pass. Capacity, 12 MPH Max Speed and 15 Pass./12 Min. Demand Rate**	**Vehicle Fleet and Operating Route**	System Length (Mi.)	Number of Stations/Stops	In-Service Veh. Operating Fleet	Avg. Headway (min.)
		1.63	10	3	4.56
	Vehicle/System Capacity and Mileage	Vehicle Capacity (passengers)	Pk. Interval Throughput Capacity	Route Hourly Throughput Capacity (pphpd)	Fleet Vehicle-Miles Traveled per Hour
		6	16	79	21.36
	Passenger Activity & LOS	Peak Interval Duration (min.)	Pk. Interval Surge Flow at Metro	Average Service Waiting Time (min.)	Typical Passenger Trip Time (min.)
		12	15	2.28	9.13
Case Study #2 **12 Pass. Capacity, 12 MPH Max Speed and 15 Pass./12 Min. Demand Rate**	**Vehicle Fleet and Operating Route**	System Length (KM)	Number of Stations/Stops	In-Service Veh. Operating Fleet	Avg. Headway (min.)
		1.63	10	2	6.85
	Vehicle/System Capacity and Mileage	Vehicle Capacity (passengers)	Pk. Interval Throughput Capacity	Route Hourly Throughput Capacity (pphpd)	Fleet Vehicle-Miles Traveled per Hour
		12	21	105	14.24
	Passenger Activity & LOS	Peak Interval Duration (min.)	Pk. Interval Surge Flow at Metro	Average Service Waiting Time (min.)	Typical Passenger Trip Time (min.)
		12	15	3.42	10.27

Case Studies #3 and #4

CASE STUDY DESCRIPTION	Plng. Criteria Classification	System Parameters and Characteristics			
Case Study #3 **6 Pass. Capacity, 20 MPH Max Speed and 15 Pass./12 Min. Demand Rate**	**Vehicle Fleet and Operating Route**	System Length (Mi.)	Number of Stations/Stops	In-Service Veh. Operating Fleet	Avg. Headway (min.)
		1.63	10	3	4.03
	Vehicle/System Capacity and Mileage	Vehicle Capacity (passengers)	Pk. Interval Throughput Capacity	Route Hourly Throughput Capacity (pphpd)	Fleet Vehicle-Miles Traveled per Hour
		6	18	89	24.21
	Passenger Activity & LOS	Peak Interval Duration (min.)	Pk. Interval Surge Flow at Metro	Average Service Waiting Time (min.)	Typical Passenger Trip Time (min.)
		12	15	2.01	8.06
Case Study #4 **12 Pass. Capacity, 20 MPH Max Speed and 15 Pass./12 Min. Demand Rate**	**Vehicle Fleet and Operating Route**	System Length (KM)	Number of Stations/Stops	In-Service Veh. Operating Fleet	Avg. Headway (min.)
		1.63	10	2	6.04
	Vehicle/System Capacity and Mileage	Vehicle Capacity (passengers)	Pk. Interval Throughput Capacity	Route Hourly Throughput Capacity (pphpd)	Fleet Vehicle-Miles Traveled per Hour
		12	24	119	16.14
	Passenger Activity & LOS	Peak Interval Duration (min.)	Pk. Interval Surge Flow at Metro	Average Service Waiting Time (min.)	Typical Passenger Trip Time (min.)
		12	15	3.02	9.06

Case Studies #5 and #6

CASE STUDY DESCRIPTION	Plng. Criteria Classification	System Parameters and Characteristics			
Case Study #5 **6 Pass. Capacity, 12 MPH Max Speed and 30 Pass./12 Min. Demand Rate**	**Vehicle Fleet and Operating Route**	System Length (Mi.)	Number of Stations/Stops	In-Service Veh. Operating Fleet	Avg. Headway (min.)
		1.63	10	6	2.28
	Vehicle/System Capacity and Mileage	Vehicle Capacity (passengers)	Pk. Interval Throughput Capacity	Route Hourly Throughput Capacity (pphpd)	Fleet Vehicle-Miles Traveled per Hour
		6	32	158	42.72
	Passenger Activity & LOS	Peak Interval Duration (min.)	Pk. Interval Surge Flow at Metro	Average Service Waiting Time (min.)	Typical Passenger Trip Time (min.)
		12	30	1.14	7.99
Case Study #6 **12 Pass. Capacity, 12 MPH Max Speed and 30 Pass./12 Min. Demand Rate**	**Vehicle Fleet and Operating Route**	System Length (KM)	Number of Stations/Stops	In-Service Veh. Operating Fleet	Avg. Headway (min.)
		1.63	10	3	4.56
	Vehicle/System Capacity and Mileage	Vehicle Capacity (passengers)	Pk. Interval Throughput Capacity	Route Hourly Throughput Capacity (pphpd)	Fleet Vehicle-Miles Traveled per Hour
		12	32	158	21.36
	Passenger Activity & LOS	Peak Interval Duration (min.)	Pk. Interval Surge Flow at Metro	Average Service Waiting Time (min.)	Typical Passenger Trip Time (min.)
		12	30	2.28	9.13

Case Studies #7 and #8

CASE STUDY DESCRIPTION	Plng. Criteria Classification	System Parameters and Characteristics			
Case Study #7	Vehicle Fleet and Operating Route	System Length (Mi.)	Number of Stations/Stops	In-Service Veh. Operating Fleet	Avg. Headway (min.)
		1.63	10	5	2.42
6 Pass. Capacity, 20 MPH Max Speed and 30 Pass./12 Min. Demand Rate	Vehicle/System Capacity and Mileage	Vehicle Capacity (passengers)	Pk. Interval Throughput Capacity	Route Hourly Throughput Capacity (pphpd)	Fleet Vehicle-Miles Traveled per Hour
		6	30	149	40.34
	Passenger Activity & LOS	Peak Interval Duration (min.)	Pk. Interval Surge Flow at Metro	Average Service Waiting Time (min.)	Typical Passenger Trip Time (min.)
		12	30	3.65	9.69
Case Study #8	Vehicle Fleet and Operating Route	System Length (KM)	Number of Stations/Stops	In-Service Veh. Operating Fleet	Avg. Headway (min.)
		1.63	10	3	4.03
12 Pass. Capacity, 20 MPH Max Speed and 30 Pass./12 Min. Demand Rate	Vehicle/System Capacity and Mileage	Vehicle Capacity (passengers)	Pk. Interval Throughput Capacity	Route Hourly Throughput Capacity (pphpd)	Fleet Vehicle-Miles Traveled per Hour
		12	36	179	24.21
	Passenger Activity & LOS	Peak Interval Duration (min.)	Pk. Interval Surge Flow at Metro	Average Service Waiting Time (min.)	Typical Passenger Trip Time (min.)
		12	30	2.01	8.06

Case Studies #9 and #10

CASE STUDY DESCRIPTION	Plng. Criteria Classification	System Parameters and Characteristics			
Case Study #9 **6 Pass. Capacity, 12 MPH Max Speed and 45 Pass./12 Min. Demand Rate**	**Vehicle Fleet and Operating Route**	System Length (Mi.)	Number of Stations/Stops	In-Service Veh. Operating Fleet	Avg. Headway (min.)
		1.63	10	9	1.52
	Vehicle/System Capacity and Mileage	Vehicle Capacity (passengers)	Pk. Interval Throughput Capacity	Route Hourly Throughput Capacity (pphpd)	Fleet Vehicle-Miles Traveled per Hour
		6	47	237	64.08
	Passenger Activity & LOS	Peak Interval Duration (min.)	Pk. Interval Surge Flow at Metro	Average Service Waiting Time (min.)	Typical Passenger Trip Time (min.)
		12	45	0.76	7.61
Case Study #10 **12 Pass. Capacity, 12 MPH Max Speed and 45 Pass./12 Min. Demand Rate**	**Vehicle Fleet and Operating Route**	System Length (KM)	Number of Stations/Stops	In-Service Veh. Operating Fleet	Avg. Headway (min.)
		1.63	10	5	2.74
	Vehicle/System Capacity and Mileage	Vehicle Capacity (passengers)	Pk. Interval Throughput Capacity	Route Hourly Throughput Capacity (pphpd)	Fleet Vehicle-Miles Traveled per Hour
		12	53	263	35.60
	Passenger Activity & LOS	Peak Interval Duration (min.)	Pk. Interval Surge Flow at Metro	Average Service Waiting Time (min.)	Typical Passenger Trip Time (min.)
		12	45	1.37	8.22

Case Studies #11 and #12

CASE STUDY DESCRIPTION	Plng. Criteria Classification	System Parameters and Characteristics			
Case Study #11 **6 Pass. Capacity, 20 MPH Max Speed and 45 Pass./12 Min. Demand Rate**	**Vehicle Fleet and Operating Route**	System Length (Mi.)	Number of Stations/Stops	In-Service Veh. Operating Fleet	Avg. Headway (min.)
		1.63	10	8	1.51
	Vehicle/System Capacity and Mileage	Vehicle Capacity (passengers)	Pk. Interval Throughput Capacity	Route Hourly Throughput Capacity (pphpd)	Fleet Vehicle-Miles Traveled per Hour
		6	48	238	64.55
	Passenger Activity & LOS	Peak Interval Duration (min.)	Pk. Interval Surge Flow at Metro	Average Service Waiting Time (min.)	Typical Passenger Trip Time (min.)
		12	45	0.76	6.80
Case Study #12 **12 Pass. Capacity, 20 MPH Max Speed and 45 Pass./12 Min. Demand Rate**	**Vehicle Fleet and Operating Route**	System Length (KM)	Number of Stations/Stops	In-Service Veh. Operating Fleet	Avg. Headway (min.)
		1.63	10	4	3.02
	Vehicle/System Capacity and Mileage	Vehicle Capacity (passengers)	Pk. Interval Throughput Capacity	Route Hourly Throughput Capacity (pphpd)	Fleet Vehicle-Miles Traveled per Hour
		12	48	238	32.28
	Passenger Activity & LOS	Peak Interval Duration (min.)	Pk. Interval Surge Flow at Metro	Average Service Waiting Time (min.)	Typical Passenger Trip Time (min.)
		12	45	1.51	7.55

Exhibit C Capital/Project Cost Summary Tables
For Selected Case Studies

Exhibit C Capital/Project Cost Summary Tables for Selected Case Studies

Case Study #1 – 4 Vehicle Fleet, 12 MPH Speed, 6 Passenger Capacity, 15 Passenger/Pk. Period Demand

Subsystem	
Transitway/Roadway	$0
Vehicles	$1,508,815
ITS/System Automated Control Infrastructure	$277,568
Propulsion	$0
Communications	$281,893
Battery Charging Power Supply	$111,198
Station Equipment	$76,729
Maintenance Area Provisions	$122,809
Spare Parts & Supplies	$56,697
Intangible Project Support	$1,344,357
Contingency	$378,007
Total Estimated Cost	**$4,158,072**

Case Study #7 – 6 Vehicle Fleet, 20 MPH Speed, 6 Passenger Capacity, 30 Passenger/Pk. Period Demand

Subsystem	
Transitway/Roadway	$0
Vehicles	$2,263,222
ITS/System Automated Control Infrastructure	$312,173
Propulsion	$0
Communications	$281,893
Battery Charging Power Supply	$111,198
Station Equipment	$76,729
Maintenance Area Provisions	$122,809
Spare Parts & Supplies	$68,866
Intangible Project Support	$1,354,491
Contingency	$459,138
Total Estimated Cost	**$5,050,520**

Case Study #11 – 10 Vehicle Fleet, 20 MPH Speed, 6 Passenger Capacity, 45 Passenger/Pk. Period Demand

Subsystem	
Transitway/Roadway	$0
Vehicles	$3,772,037
ITS/System Automated Control Infrastructure	$381,385
Propulsion	$0
Communications	$281,893
Battery Charging Power Supply	$111,198
Station Equipment	$76,729
Maintenance Area Provisions	$122,809
Spare Parts & Supplies	$93,204
Intangible Project Support	$1,374,760
Contingency	$621,402
Total Estimated Cost	**$6,835,417**

Case Study #12 – 5 Vehicle Fleet, 20 MPH Speed, 12 Passenger Capacity, 45 Passenger/Pk. Period Demand

Subsystem	
Transitway/Roadway	$0
Vehicles	$1,886,019
ITS/System Automated Control Infrastructure	$294,871
Propulsion	$0
Communications	$281,893
Battery Charging Power Supply	$111,198
Station Equipment	$76,729
Maintenance Area Provisions	$122,809
Spare Parts & Supplies	$62,782
Intangible Project Support	$1,349,424
Contingency	$418,572
Total Estimated Cost	**$4,604,296**

Exhibit D Operations and Maintenance Cost Summary Tables For Selected Case Studies

Exhibit D Operations and Maintenance Cost Summary Tables for Selected Case Studies

Case Study #1

Veh. Fleet - Oprtg + Spares = 4
No. of Passenger Stations = 2
No. of Station Vehicle Berths = 2

O&M Cost Components	% of Total Cost	O&M Cost Adjustment	Component Cost Amount
Operations Staff Payroll	35%	1.33	$541,173
Maintenance/Engineering	28%	0.85	$436,050
Energy	5%	1.50	$73,636
Subtotal	**67%**	--	$1,050,860
Veh. Fleet Depreciation - 8Yrs	33%	1.00	$513,000
Total Incl. Depreciation	**100%**		$1,563,860

Fleet Operations Maintenance and Energy Statistics

Case Study Operating Fleet (Excluding Spares) =	3	Veh.
Equivalent Hrs /Day of Full Fleet Operations =	10	Hrs
Veh-Mi Traveled per Vehicle Operational Hour =	7.1	MPH
Veh-Mi Traveled per Vehicle Operational Day =	71.2	Veh-Mi
Total Fleet Accumulative Veh-Miles per Day =	213.6	Veh/Mi

Case Study #7

Veh. Fleet - Oprtg + Spares = 6
No. of Passenger Stations = 2
No. of Station Vehicle Berths = 2

O&M Cost Components	% of Total Cost	O&M Cost Adjustment	Component Cost Amount
Operations Staff Payroll	44%	2.00	$811,760
Maintenance/Engineering	24%	0.85	$436,050
Energy	4%	1.50	$73,636
Subtotal	**72%**	--	$1,321,446
Veh. Fleet Depreciation - 8Yrs	28%	1.00	$513,000
Total Incl. Depreciation	**100%**		$1,834,446

Fleet Operations Maintenance and Energy Statistics

Case Study Operating Fleet (Excluding Spares) =	5	Veh.
Equivalent Hrs /Day of Full Fleet Operations =	10	Hrs
Veh-Mi Traveled per Vehicle Operational Hour =	8.1	MPH
Veh-Mi Traveled per Vehicle Operational Day =	80.7	Veh-Mi
Total Fleet Accumulative Veh-Miles per Day =	403.4	Veh/Mi

Cast Study #11

Veh. Fleet - Oprtg + Spares = 9
No. of Passenger Stations = 2
No. of Station Vehicle Berths = 2

O&M Cost Components	% of Total Cost	O&M Cost Adjustment	Component Cost Amount
Operations Staff Payroll	54%	3.00	$1,217,640
Maintenance/Engineering	19%	0.85	$436,050
Energy	3%	1.50	$73,636
Subtotal	**77%**	--	$1,727,326
Veh. Fleet Depreciation - 8Yrs	23%	1.00	$513,000
Total Incl. Depreciation	**100%**		$2,240,326

Fleet Operations Maintenance and Energy Statistics

Case Study Operating Fleet (Excluding Spares) =	8	Veh.
Equivalent Hrs /Day of Full Fleet Operations =	10	Hrs
Veh-Mi Traveled per Vehicle Operational Hour =	8.1	MPH
Veh-Mi Traveled per Vehicle Operational Day =	80.7	Veh-Mi
Total Fleet Accumulative Veh-Miles per Day =	645.5	Veh/Mi

Cast Study #12

Veh. Fleet - Oprtg + Spares = 5
No. of Passenger Stations = 2
No. of Station Vehicle Berths = 2

O&M Cost Components	% of Total Cost	O&M Cost Adjustment	Component Cost Amount
Operations Staff Payroll	40%	1.67	$676,467
Maintenance/Engineering	26%	0.85	$436,050
Energy	4%	1.50	$73,636
Subtotal	**70%**	--	$1,186,153
Veh. Fleet Depreciation - 8Yrs	30%	1.00	$513,000
Total Incl. Depreciation	**100%**		$1,699,153

Fleet Operations Maintenance and Energy Statistics

Case Study Operating Fleet (Excluding Spares) =	4	Veh.
Equivalent Hrs /Day of Full Fleet Operations =	10	Hrs
Veh-Mi Traveled per Vehicle Operational Hour =	8.1	MPH
Veh-Mi Traveled per Vehicle Operational Day =	80.7	Veh-Mi
Total Fleet Accumulative Veh-Miles per Day =	322.8	Veh/Mi