Texas Southern University

Automated Vehicle

Final Report

July 2020

Center for Transportation Training and Research

TSU H-GAC METRO

Automated Vehicle Team

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Special thanks to METRO's Jim Archer, Kenneth Brown and Steven Washington for bus ridership data and Phase 2 Route Analysis.

We also appreciate contributions of Mathew G. Shirk from Idaho National Laboratory to the battery utilization data and analyses.

Contents

Introduction

Texas Southern University (TSU) is a state-supported, Historical Black College and University (HBCU) of higher learning located in the Third Ward neighborhood of Houston. The institution began in 1927 as the Colored Junior College by action of the Houston Public School Board. Thereafter, the fiftieth Texas State Legislature passed a bill establishing a "Negro University with a law school to be located in Houston". TSU now occupies a 145-acre, forty-six building campus just southeast of downtown Houston. It includes an FM radio station, a physical education complex with a 7,200-seat arena, a performance theater, several dormitories, nearby apartment complexes, and 11 colleges and schools.

The University offers bachelor's, master's and doctoral degree programs in the following academic colleges and schools: the College of Liberal Arts and Behavioral Sciences; the College of Pharmacy and Health Sciences; the College of Science and Technology; the College of Education; the Barbara Jordan-Mickey Leland School of Public Affairs; the School of Communication; the Thurgood Marshall School of Law; the Jesse H. Jones School of Business; the Thomas Freeman Honors College; the College of Continuing Education and the Graduate School. Other programmatic emphases are found in the Center for Excellence in Urban Education and the Center for Transportation Training and Research. The university is staffed by approximately 1,000 faculty members and support personnel. It has more than 9,500 students, representing diverse backgrounds and a number of international students. Figures 1 and 2 show the TSU entrance and the Tiger Walk, a pedestrian promenade that runs through the center of campus.

Figure 1. TSU Entrance

Figure 2. TSU Tiger Walk

Discussion about the TSU Automated Vehicle (AV) shuttle began as part of a larger concept originally known as the University District Automated Vehicle project. The idea was to service TSU, the METRO light rail Purple Line station, the University of Houston, and eventually METRO's Eastwood Transit Center. As the AV Team continued planning steps, the decision quickly emerged to begin with the first ½ mile prototype operation on the TSU Tiger Walk. The team is pleased to have 8 months of operational data, including during the hot summer months of July and August and during a rare Houston October freeze. The primary purposes of the pilot project were to:

- Gain insight into the operational characteristics of the AV during fair and inclement weather,
- Acquire knowledge of battery capabilities during temperature variations, and
- Assess perspectives of riders and vehicle attendants (the term attendant is intentional to show variation in task requirements in contrast to a METRO Operator).

The AV pilot program, utilizing an EasyMile Gen 2 vehicle, commenced in the summer semester of 2019, initiating June 5 and operating through February 25, 2020. During the summer session about 2000 students are enrolled in classes. There are not many events that occur during the summer besides two children's camps and student orientation. There is therefore less congestion and anticipated lower ridership compared to spring and fall semesters. This more relaxed atmosphere allowed the AV to begin operation in a less intensively congested environment than possible during the regular academic terms.

In comparison, during the fall and spring semesters, the campus is well-populated, and hosts a number of events. Throughout the school year, the campus hosts basketball matches, volleyball matches, Spring Fest, Homecoming, commencement, student organization drives, political rallies, debates, stage plays, and recruitment tours. The AV's daily operation followed a schedule of 8 a.m. to 2 p.m. and 5 p.m. to 8 p.m. for fall and spring and 8 a.m. until 4 p.m. during summer. The schedule was established based on the campus population for the semester as well as peak volume expectations, such as the end of class or lunch time.

Major internal events during the Fall semester include Homecoming week and graduation commencement, which bring families and alumni to campus. Major events during the Spring semester include the Greek letter organization New Member Presentations, bringing families of the new members from near and far, basketball matches, and the Spring Fest week, which comprises several student activities, supplemented by participation of students from other guest schools. Many of these events are set up on the Tiger Walk and the AV did not operate during these events.

Smaller and seasonal events throughout the school year include guest speakers invited by various student organizations to address students regarding different topics, stage plays, and political debates and rallies. Service was suspended on February 25, 2020, when the National Highway Transportation Safety Administration (NHTSA) issued an emergency stop on a similar EasyMile AV in Columbus, Ohio, that slightly injured a passenger. NHTSA required each AV operation to submit a safety plan prior to reauthorization of operations. Before that could occur, the City of Houston and Harris County issued stay-at-home orders due to COVID-19 threats on March 18, 2020. TSU suspended in-person classes for the duration of the spring semester.

The general findings of the AV pilot are as follows:

- Vehicle performance was fine during fair weather and in light rain; however, it was unable to maintain operation during a heavy rain.
- Battery life was significantly impacted by hot weather, engaging the air conditioner or heater, and use of USB ports provided within the vehicle.
- Acceptance from the student, faculty and staff and visitor populations were enthusiastic and people were generally not intimidated by the automated nature of the vehicle.

Initial Operational and Planning and Decisions

There were several important aspects for consideration, including battery charging capacity, vehicle design, station siting, and vehicle storage location. Another critical aspect was whether or not the vehicle would be configured for bi-directional operation and whether there would be passenger boarding doors on only one side or on both sides of the vehicle. These aspects are addressed below in terms of the final design utilized in the deployment of the EasyMile EZ10 Gen 2 vehicle on the TSU campus. Additional details relating to initial operational and planning decisions are in **Appendix B**.

Battery Charging Optional Designs

The first aspect concerned the vehicle's battery-electric propulsion system and the issue of electric vehicle's operational range due to battery–charge limitation – a significant matter for electric vehicles in transit service. The use of battery-electric vehicle propulsion was found to be a common feature of the vehicle technologies that were considered for the TSU AV Shuttle project. This led to an assessment of the optional design approaches that provide the means to charge batteries of all the vehicles in the operating fleet when operations are continuous throughout the day.

Different approaches were found in the 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 support facilities. These factors have a direct bearing on the cost of the total fleet size and electrical charging infrastructure.

Vehicle Configuration

Also considered in the early planning phase 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). Other vehicle design features that were assessed during the conceptual planning phase were the vehicle turning radius and the provisions for either ramp deployment from within the vehicle chassis for wheelchair access or a vehicle design capable of precision docking with the edge of a raised platform level, from which the entry of wheelchairs was a simple "roll on/roll off" maneuver by the passenger in the wheelchair.

These vehicle design features 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 that would reverse its travel direction through a 180 degree turn at either end of the Tiger Walk corridor before or after the end-of-line station. This operational approach, when combined with a vehicle design with doors on only one side of the vehicle, had a significant effect on station locations and resulted in 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.

Following a request for qualifications issued by METRO, the agency contracted with First Transit for the Easy Mile Gen 2 vehicle to serve as TSU's AV Shuttle. Various alignment and station configurations were investigated after the First Transit/EasyMile partnership was selected. The operation selected traversed the Tiger Walk and made a loop route with a 180 degree turn at each end.

Station Placement

The assessment of person-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. Observing class beginning and ending times, along with the major campus activity generators, led to the decision to provide three stations on the route. The east end station was placed proximate to the Library and Resource Center, the center of campus station was placed at the Sterling Student Center/Hannah Hall main administration building, and the western station was placed in front of the Leonard H.O. Spearman Building/Health and Physical Education Arena (Figure 3).

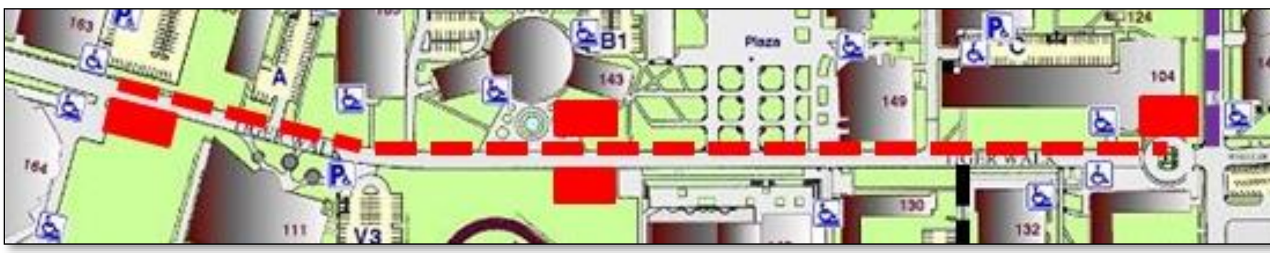

Figure 3. TSU AV Route and Stations

Storage/Charging and Operational Support Facilities

After the AV shuttle contractor (First Transit) was selected, assessment of potential locations which could serve as the vehicle storage and operational support facility began. EasyMile defined the specific power supply requirements for vehicle battery charging. The selection process deliberations concerning the vehicle storage location involved the TSU Administration, TSU Facilities, TSU Security/Police, Houston METRO and the Contractor – First Transit/EasyMile.

Required clearances for the vehicle height proved to be one of the most constraining parameters for a suitable storage location, followed by the proximity to the operating route. It is important to recognize that the National Highway Transportation Safety Administration's (NHTSA) approval for an AV operation 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 an AV Shuttle storage/charging and operations support facility was fundamentally determined by the size of the vehicle fleet. For the single vehicle deployment in the TSU Shuttle project, several possible spaces were considered. Insight into appropriate facility provisions was gained by this process, particularly with respect to the building door size/clearances, as well as the functional utility of the location. Multiple locations were considered which are described in **Appendix A**.

PROXIMITY OF SUPPORT FACILITIES TO OPERATING ROUTE: Ultimately, a vehicle bay that was accessible from the south side of the Central Plant and very near (within 300 yards) to the Tiger Walk operating route proved to be the proper solution for the vehicle storage and charging location (Figure 4). In addition, it was big enough to also allow maintenance activity to occur on site, and it provided sufficient space for secure storage of the contractor’s materials, equipment and spare parts. Most importantly, the Central Plant vehicle bay had electrical power provisions for vehicle recharging requirements. Moreover, the location had enough space that could also accommodate more vehicles should an extension to the METRO Purple Line light rail station and University of Houston be pursued. The selected vehicle storage location was made available by the by TSU Facilities Department, with METRO covering reasonable expenses for its conversion to provide suitable charging stations and accommodations. This satisfied EasyMile’s requests and proved to be a key part of the final decision on the storage location (EasyMile, 6/21/2018).

Figure 4. Central Plant Storage Location, Exterior and Interior Storage/Charging

ELECTRIC VEHICLE CHARGING ACCOMMODATIONS*:* The stated power supply requirements that were provided to the project team by EasyMile became the basis for the power supply circuit installed within the vehicle storage bay. For battery charging capabilities, the voltage and amperage limitations of the existing power supply determined whether the charging equipment could accommodate either a slow charging rate or a more rapid charging rate. Due to the fact that the TSU AV Shuttle deployment was treated as a demonstration pilot with only a temporary waiver being offered by NHTSA for “testing purposes," the additional cost necessary to incur in order to upgrade the power supply circuits in the Central Plant storage bay such that they would be suitable for a rapid-charge capability was not justified.

The EasyMile-specified electrical provisions for the storage area were a 240V AC 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 receptacle. Figure 5 shows the power supply provisions and the vehicle as it was positioned in its charging location.

Figure 5. Power Supply Electrical Provisions for AV Battery Charging and Monitoring

Detailed Description of Travel Environment

The TSU campus is largely linear, stretching almost 2 miles east to west and approximately ½ mile north to south. The Tiger Walk bisects the campus and traverses almost its entire length. Residential housing and the Library and Learning Center dominate the eastern portion of the campus. The Health and Physical Education arena (HPE), Spearman Technology building and New Science building anchor the west. Administration, classrooms, the Sterling Student Life Center, the Recreation Center and the post office are in between. Initial operation during the summer of 2019 reflected the station scenario with a location at each end of campus and one central location at the Sterling Student Life Center. Multiple requests for an additional stop at the campus post office and recreation building resulted in a 4th station being added for that location at the beginning of the fall semester (Figure 6). This resulted in the AV shuttle service having four stops to serve students, faculty, staff, and visitors, as follows and depicted in Figure 6:

- Spearman Technology Building/H & PE arena
- TSU campus US Post Office/Student Recreational Center
- Sterling Student Life Center
- TSU Library Learning Center

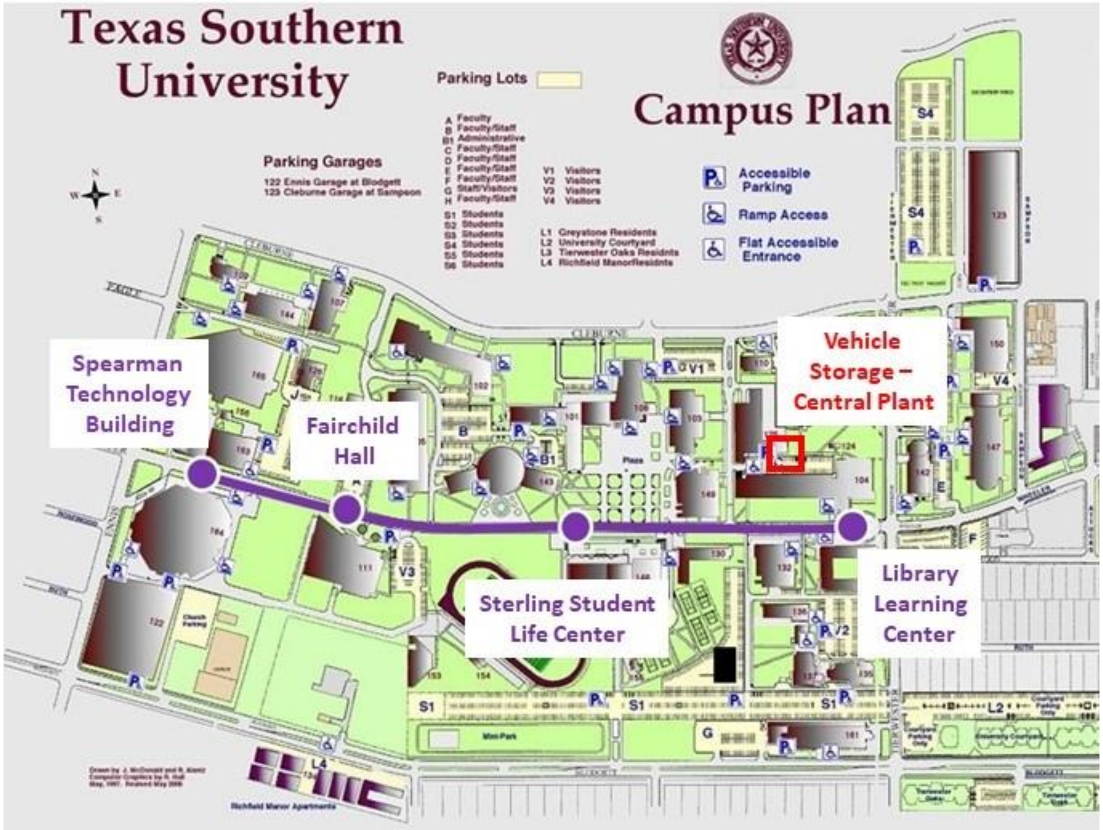

Figure 6. Tiger Walk and Station Locations

PARKING AND PUBLIC TRANSPORTATION ON CAMPUS: Students, faculty, staff and visitors have a few options for parking on campus, including the West Garage, the East Garage, and a Student Lot located on Blodgett Street, all shown below in Figure 7. The West Garage has a total of 1,039 parking spaces; 107 are designated for faculty and the remaining 932 spaces allotted to students and visitors. The East Garage has 1,323 total parking spaces; 144 spaces for faculty and 1,179 for students. The Student Lot with the entrance from Blodgett Street has a total of 297 parking spaces, all for students except for five that are contracted. Between these three parking facilities there are a combined number of 2,659 parking spaces. There are also several smaller lots for students and staff adjacent to Tierwester and Cleburne.

METRO operates several bus routes within the vicinity of the TSU campus, including the 25 Richmond (which runs along Blodgett on the south side of campus) and the 4 Beechnut (which runs along the western and northern edges of campus). The route of the 4 Beechnut is shown in Figure 7.

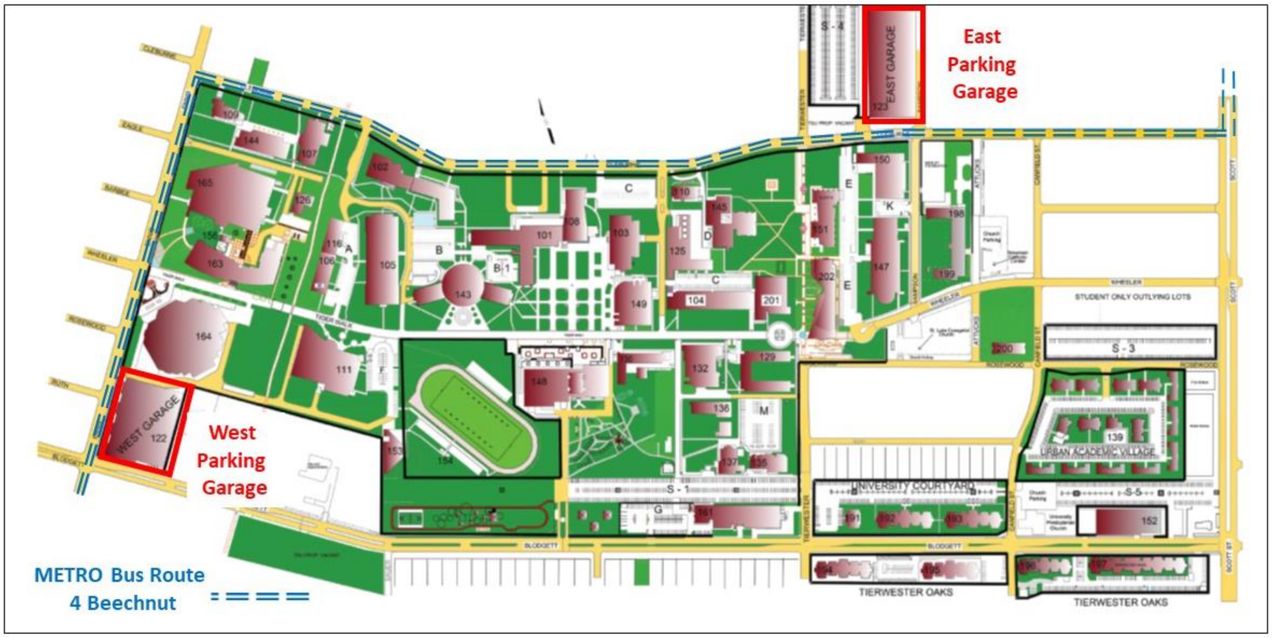

Figure 7. TSU Campus East and West Garages and METRO 4 Beechnut Bus Route

Table 1 shows distances and walking times to and between AV shuttle stops. The Spearman Technology Building AV stop is the nearest stop to both the West Parking Garage as well as the 4 Beechnut METRO bus stop located on Ennis Street at Wheeler Avenue. The distance from the West Parking Garage to the Technology Building AV stop is 797 feet (0.15 miles) or a three-minute walk. From the METRO bus stop to the Technology building AV stop, the distance is approximately 427 feet (0.08 miles) and is roughly a two-minute walk.

Once on Texas Southern University campus, the AV route is over 2,000 feet long. The distance from the Spearman Technology building AV stop to the USPS AV stop is 453 feet (0.08 miles), or a two-minute walk; the distance from the USPS AV stop to the Sterling Student Life Center AV stop is 528 feet (0.1 miles), or a three-minute walk; and the distance from the Sterling Student Life Center AV stop to the Library Learning Center AV stop is 1,056 feet (0.2 miles), or a three-minute walk.

The TSU Library Learning Center AV stop is the nearest stop to both the East Parking Garage and the METRO bus stop located on Cleburne Street at Tierwester Street that is served by the 4 Beechnut route. The distance between the East Parking Garage and the TSU Library Learning Center AV stop is 1069 feet (0.2 miles), a five-minute walk. The distance from the METRO bus stop on Cleburne at Tierwester to the Library Learning Center AV stop is 922 feet (0.17 miles), a four-minute walk.

Table 1. Distances to and Between AV Stops

Distance to Nearest Automated Vehicle (AV) Stop			
	Feet	Miles	Minutes
METRO Route 4 Ennis @ Wheeler to Technology Building AV stop	427	0.08	2
West Garage to Technology Building AV stop	797	0.15	3
Technology Building AV stop to Post Office AV stop	453	0.08	2
Post Office AV stop to Student Center AV stop	528	0.1	3
Student Center AV stop to Library Learning Center AV stop	1056	0.2	3
Library Learning Center AV stop to East Garage	1069	0.2	5
METRO Route 4 Cleburne @ Tierwester to Library Learning Center AV stop	922	0.17	4

METRO RIDERSHIP*:* Table 2 shows October 2019 daily ridership from the METRO route 4 Beechnut, which begins on the Westpark Tollway slightly inside SH 6, extends past TSU and the University of Houston, and ends at the Eastwood Transit Center at IH-45. October 2019 ridership figures were surveyed because this month generally sees the highest ridership on the entire METRO system. Three corners proximate to Stop 1611 and 1618 are owned by TSU, and the other corner is the edge of residential housing project owned by the City of Houston. Two corners proximate to stops 2136 and 2141 are owned by TSU. The other two corners are single family residential units. There is no way to be certain of the distribution of trips to TSU, but it is likely most patrons of these stops are traveling to TSU, as there is another stop for the 4 Beechnut along Cleburne that would better serve the majority and midpoint of the residential housing project. One day's anecdotal and casual observance of patrons debarking at Ennis and Wheeler showed all users headed to TSU.

Table 2. METRO Ridership at Stops Proximate to TSU October 2019

Bus Stop ID	Stop	Direction	On	Off
1611	Cleburne St @ Tierwester St	WB	33	13
2141	Ennis St @ Wheeler Ave	WB	33	8
	TOTAL		**66**	**21**
2136	Ennis St @ Wheeler Ave	EB	7	33
1618	Cleburne St @ Tierwester St	EB	30	32
	TOTAL		**37**	**65**

Shuttle Ridership and Characteristics of AV Shuttle Riders

Ridership

The AV Shuttle experienced solid ridership for the entirety of the 8-month project. Operators reported the number of passengers at the end of each shift (six hours in the morning and four hours in the evening). Figure 8 shows the distribution of riders for the project duration; while it was in operation, the shuttle provided almost 7,500 individual passenger trips. Ridership was lower in the summer months, when student enrollment was modest. Once the fall semester began, ridership increased. The spike during the fall semester represents the two days when the temperature fell to 30 degrees in the morning, reaching daytime highs only in the 50s and students used the vehicle to avoid walking in the colder weather.

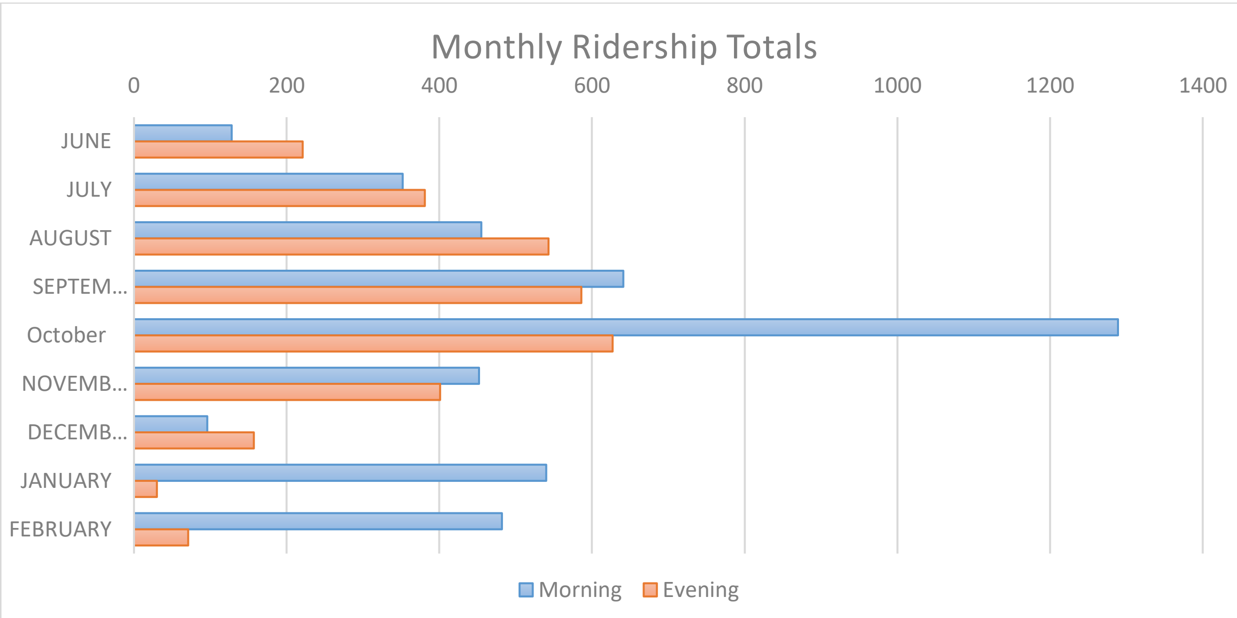

Figure 8. AV Ridership (Number of Riders per Month)

Rider Survey

Texas Southern University students, faculty, staff and visitors who rode the AV were surveyed to determine multiple characteristics, including (but not limited to):

- Their initial origin,
- Their proximity to various campus locations,
- Their travel needs while on campus, and
- Their likelihood of using the automated vehicle.

As illustrated in Figure 9 below, when asked "do you currently live on campus," out of 1105 respondents, 695 (63%) said they do not live on campus and either walk (120 or 11%), bike (11 or 0.9%), drive or ride with someone (564 or 51%); while 410 respondents (37%) said they do live on campus.

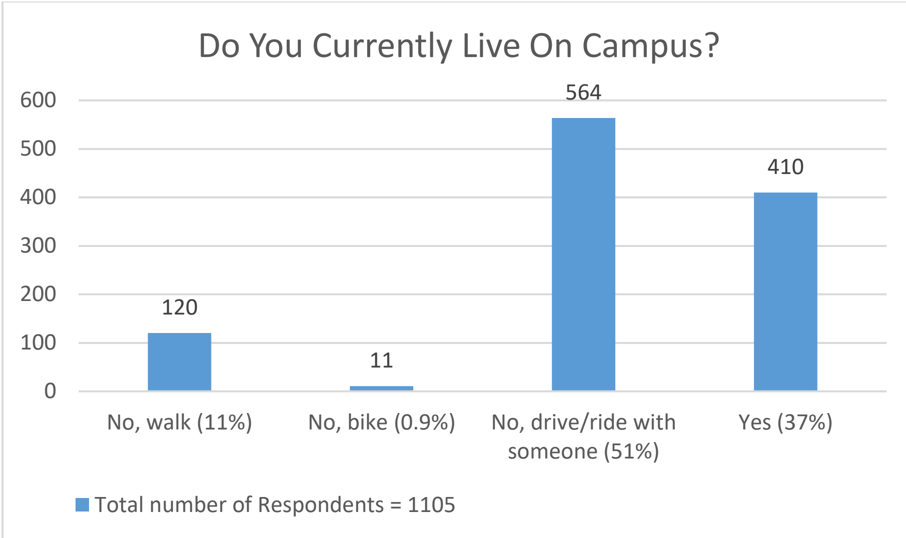

Figure 9. Riders who Live on Campus

Shown in Figure 10, when asked "if you drive to campus, where do you park," out of 1115 respondents, 318 said they park in the West Garage on Blodgett; 281 said they park in the East Garage on Cleburne; 58 responded "other," (which includes faculty parking, parking in the S-1 Lot, or parking on the street); 458 said they do not drive to campus.

When asked "when mostly on campus," out of 888 respondents, 449 said they are on campus during the day; 32 said they are on campus during the evening; and 407 people said they are on campus during both the day and the evening (Figure 11).

TSU operates another campus shuttle vehicle on the Tiger Walk, an alternatively-fueled 12-passenger tram operated by a driver. When asked if they use this vehicle (the Tiger Tram), out of 948 respondents, 98 claimed to use the campus shuttle 1-2 times a week; 110 said they used the shuttle more than twice a week; 339 said they never used the shuttle; and 401 said they used it occasionally, or on a less than weekly basis. The results are shown below in Figure 12.

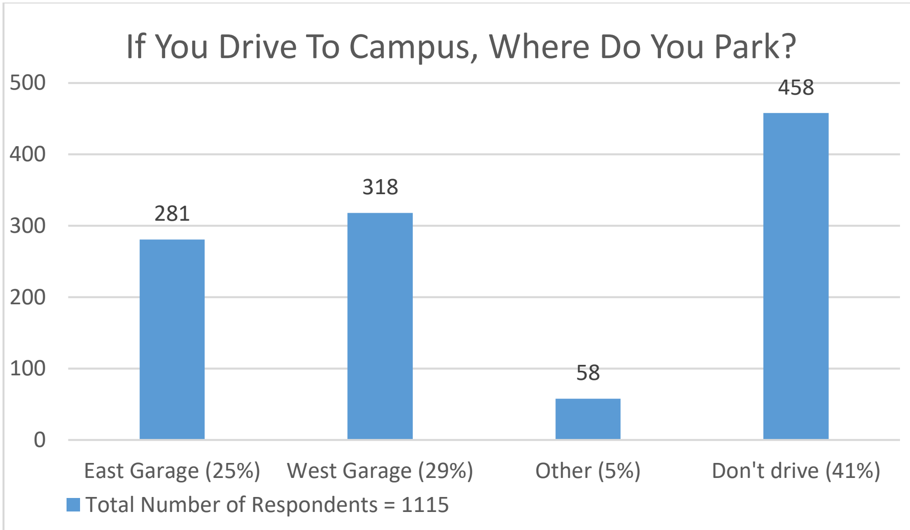

Figure 10. Rider Parking Locations

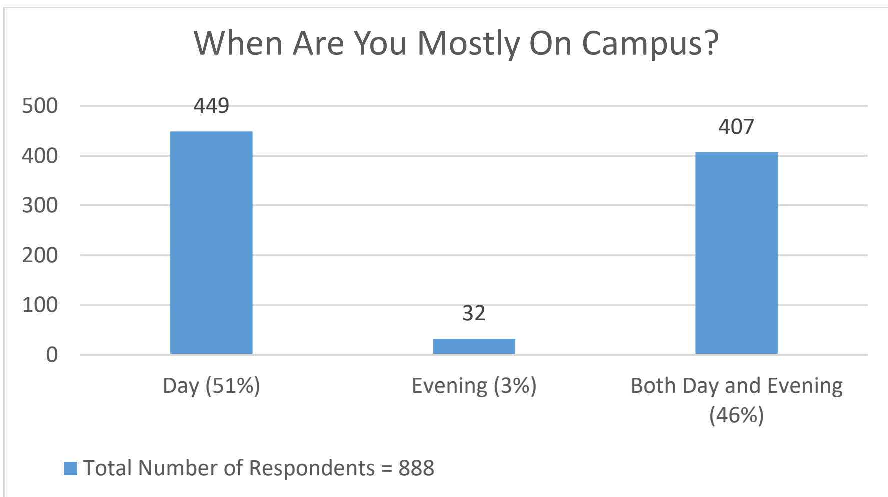

Figure 11. Users on Campus Day and Evening

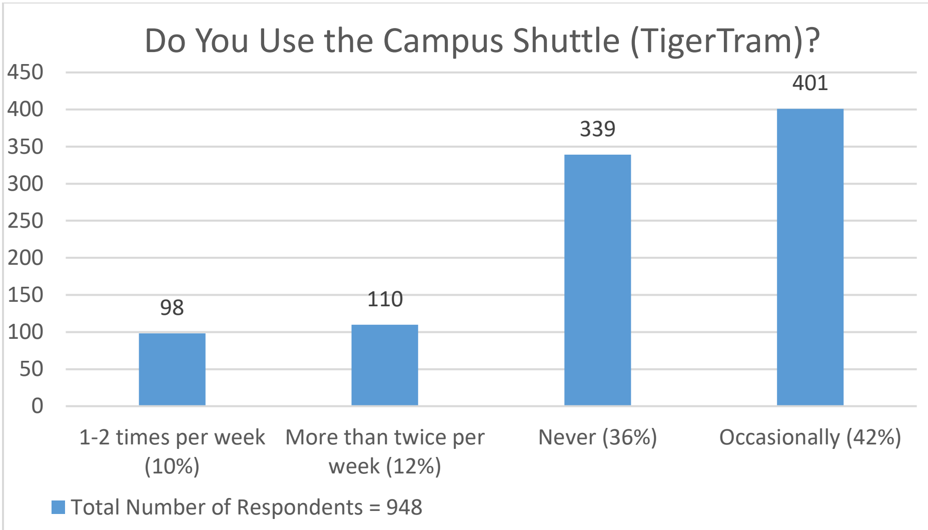

Figure 12. Use of Campus Tram

As indicated in Figure 13, when asked if they use a wheelchair or other mobility aid (i.e. cane, walker, etc.), out of 1,028 total respondents, 1,007 said no, while 21 said yes.

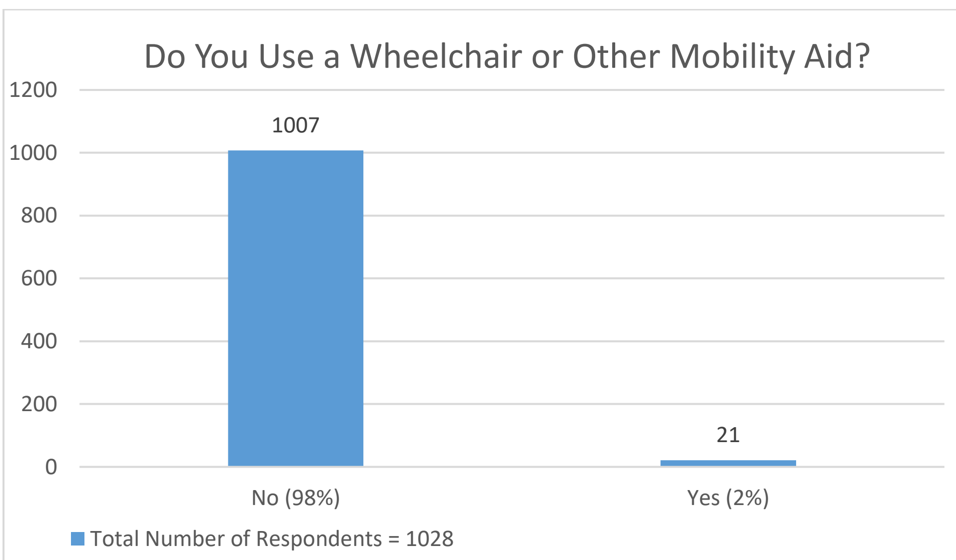

Figure 13. Use of Wheelchair or Mobility Aid

In order to understand the on-campus travel patterns of AV riders, survey respondents were asked to estimate how many times they travel between various parts of campus as well as the days of the school week they make these trips. On Mondays and Wednesdays, 661 people estimated they would travel from the east side of campus (TSU Library Learning Center) to the center of campus (Sterling Student Life Center) approximately 6,799 times, or roughly 5 round trips. On Tuesdays and Thursdays, 643 people estimated they would travel from the east side of campus to the center of campus 7,064 times, or roughly 5 round trips per respondent (Figure 14). When asked about traveling from the west side of campus to the east side of campus (Leonard H. O. Spearman Technology Building), 559 people estimated they would travel 6,772 times on Mondays and Wednesdays, roughly 6 round trips per respondent, while 514 people said they would make that trip 5,694 times, or more than 5 round trips, on Tuesdays and Thursdays (Figure 15). There are few class offerings on Fridays. The trip estimations are shown in the Table 3.

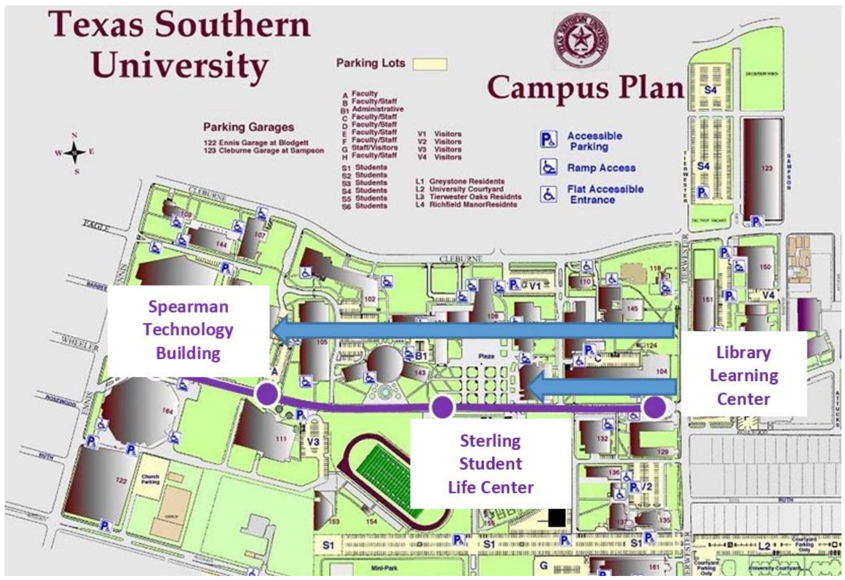

Figure 14. Student Travel from East Campus Locations

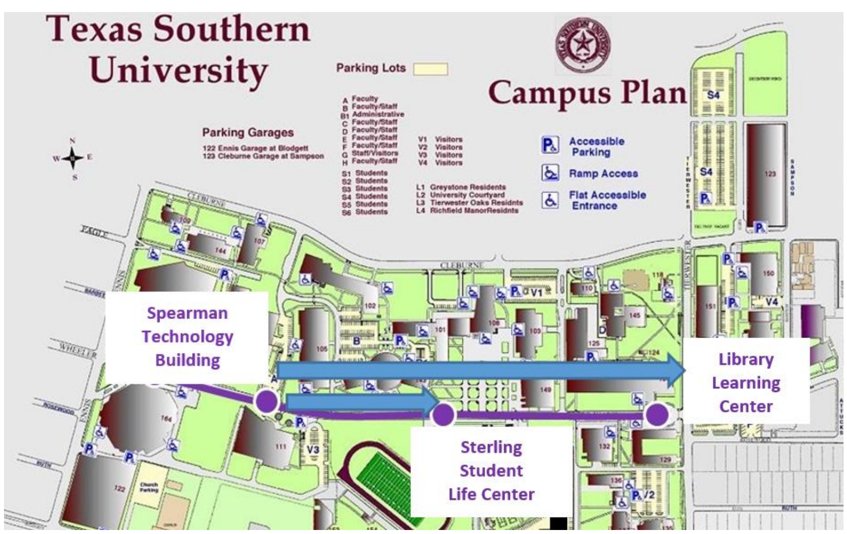

Figure 15. Travel from West Side of Campus

Table 3. Weekly On-Campus Trip Patterns of AV Shuttle Riders

Tuesday & Thursday	# of Round Trips
Library to Center	5
Library to Spearman	5
Spearman to Center	4
Spearman to Library	4

Monday & Friday	# of Round Trips
Library to Center	5
Library to Spearman	6
Spearman to Center	4
Spearman to Library	4

Physical and Operational Aspects

Because the TSU AV demonstration pilot project had only a single vehicle in operation, the operating plan for the EasyMile vehicle limited the number of service hours to allow for battery utilization or recharging. From June through August, the vehicle was scheduled to operate from 8:00 a.m. to 4:00 p.m., but often ended earlier when the battery reached the 20% power level. After fall classes began in September, the AV operated from 8:00 a.m. to 2:00 p.m., and again from 5:00 p.m. to 8:00 p.m. The hiatus between 2:00 pm and 5:00 pm 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. This approach was ideal because there is a natural reduction of student activity on campus during the middle afternoon hours, which allowed for vehicle battery charging during what would be a time of low ridership.

Phase 1 Site Physical Planning

As the demonstration pilot began operation, the precise location of boarding locations was determined through a process of testing vehicle capabilities and assessing operational impacts on the pedestrian environment. Relevant factors such as the highest trip generation locations on the campus, space accommodations for passenger waiting/queueing, and vehicle stopping locations were under constant evaluation throughout the first few months of operations.

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 making a 180-degree loop at either end of Tiger Walk, it became ineffective to only use a single boarding location for both east and west bound trips. Instead, a boarding location on the south side of the 40-foot-wide pedestrian facility for eastbound trips was established at the Sterling Student Life Center and a second queuing area on the north side of Tiger Walk for 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 tested. Knowing that access for the disabled was of very high importance, this aspect of station access was also important in the assessments.

Features of the EasyMile vehicle technology were evaluated during the initial phase with respect to the wheelchair access ramp integrated into the vehicle chassis design. Boarding locations where there is a natural raised elevation above the roadway surface level were found to be an important attribute. The raised elevation beneficially affected the ramp incline level, thereby making it easier for a person in a wheelchair to access the vehicle passenger compartment without assistance (the vehicle is ADA *accessible* but not ADA *compliant*, as explained below).

Operational Route Configuration: The basic terminology used, which indicates the way the vehicle progresses through the alignment, was defined as follows:

- *Center Lane Loop Configuration* – the vehicle would operate continuously in a unidirectional mode with a 180 degree "loop" maneuver at the east and west extents to reverse its direction. The vehicle would move near the curb for boarding and egress.
- *Center Lane Elevator Configuration* – the vehicle would operate in a bi-directional mode with a reversal of the operational head-end at each end-of-line station to travel in the opposite direction. All boarding and egress would occur on one side (north) in the center lane of the Tiger Walk.

The general corridor alignment along the TSU Tiger Walk with the loop on the east and west extents was maintained as the basic service route concept throughout the initial months of service. During the summer of 2019 the vehicle operated in the *Center Lane Loop Configuration* with 180 degree turns to reverse direction at each end of Tiger Walk. The boarding passengers would walk to board at the curb cut on the northern side of the Tiger Walk as shown in Figure 16. 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 in front of the vehicle stopping point to encourage queuing out of the main pedestrian pathway. This particular location shown in the figure was chosen because it provided good access to the vehicles from the ADA ramp coming directly from the main doorway of the Spearman Technology Building.

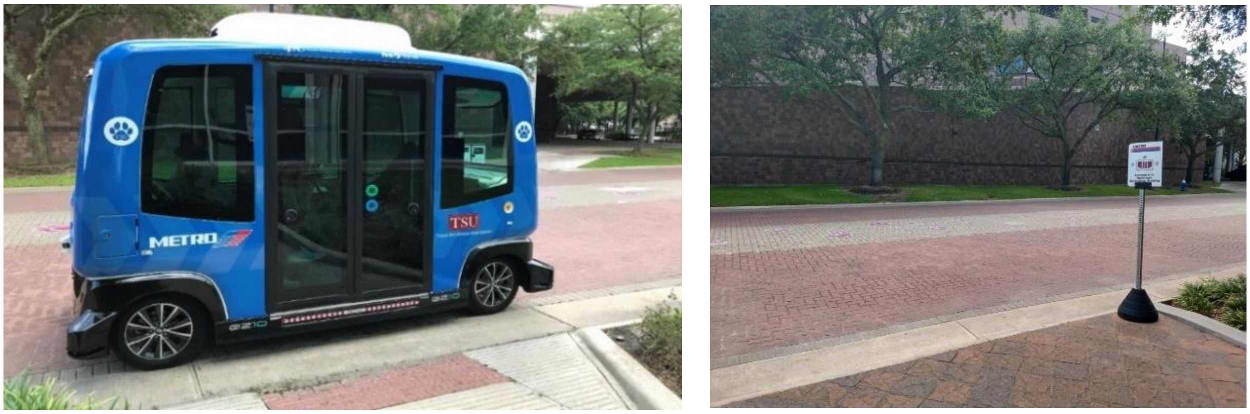

Figure 16. *Boarding Location at the North Side of the Tiger Walk Center Lane Loop Configuration*

The decision was made to implement the second option, the *Center Lane Boarding Elevator Configuration* at the beginning of the fall semester. This option provided a potential improvement to the station boarding process and provided a better location for wheelchair ramp deployment (i.e., mitigating the risks with ramp deployment into the active pedestrian lane). An ancillary benefit of this option was an up to 3-minute reduction in end-to-end running time, depending on the dwell time at stops along the path. Figure 17 provides an image of Center Lane operation and boarding along the Tiger Walk.

Figure 17. Station Stopping at the Center Lane of the Tiger Walk Elevator Configuration

Boarding for Patrons with Disabilities: The AV Gen 2 vehicle is ADA accessible but not ADA compliant. The shuttle offers a deployable ramp to aid riders in wheelchairs, on crutches, scooters, or other disabilities as they board and alight. A wheelchair "tie" allows riders to connect their wheelchairs to the vehicle; however, this "tie" is not a secure ADA compliant anchor. Space is at a premium and only one wheelchair can be accommodated on the AV. A look at surveys reveals that 21 AV riders indicated a disability. Typically, AV operators asked and then deployed the ADA accessible ramp, if a rider had a wheelchair or appeared to need help boarding the shuttle. In other instances, the AV operators report senior faculty members and persons with disabilities declining the ramp. Deployment of the ramp worked best when lowered onto the curb because that lessened the slope. An increased slope resulted when operating in “elevator” mode as the distance to the Tiger Walk pavement exceeded the distance to the curb. The survey did not ask the type or extent of disability but does shed light on the need to further consider the various needs of persons with disabilities and aging faculty.

Assessment of Vehicle Characteristics, Personnel Observations, and Battery Operation and Safety Record

Elements of the AV project were designed to assess characteristics of the vehicle’s operation, particularly battery duration under temperature extremes. It was also important to record experiences of the attendants who operated the vehicle, as well as any matters related to safety.

Vehicle Characteristics

The AV Shuttle utilized in this project is manufactured by EasyMile, based in Toulouse, France. Its technology enables autonomous vehicles to navigate safely without dedicated infrastructure. The technology consists of geo-localization, obstacle detection, safety, cybersecurity, and includes monitoring and a “black box” operations data recorder. The vehicle model for the TSU AV shuttle is the EZ10 Gen 2. It utilizes both single and multi-layer LiDAR, which is a method for measuring distances using lasers . There are sensors for the localization, navigation and obstacle detection. LiDAR, GPS, wheel odometry, and an inertial measurement unit (IMU) are utilized for localization and navigation. For obstacle detection, the vehicle uses single layer LiDAR that can see around the vehicle and 3D LiDARs in the front and rear. Figure 18 shows two localization lasers at the top of the shuttle, four 2D safety LiDARs at the four bottom corners of the shuttle, and two 3D safety LiDARs at the front and rear of the shuttle (Easy Mile, June 6, 2019). The mapping and programming for the shuttle to operate along the Tiger Walk was done on May 14, 2019 by EasyMile’s US staff.

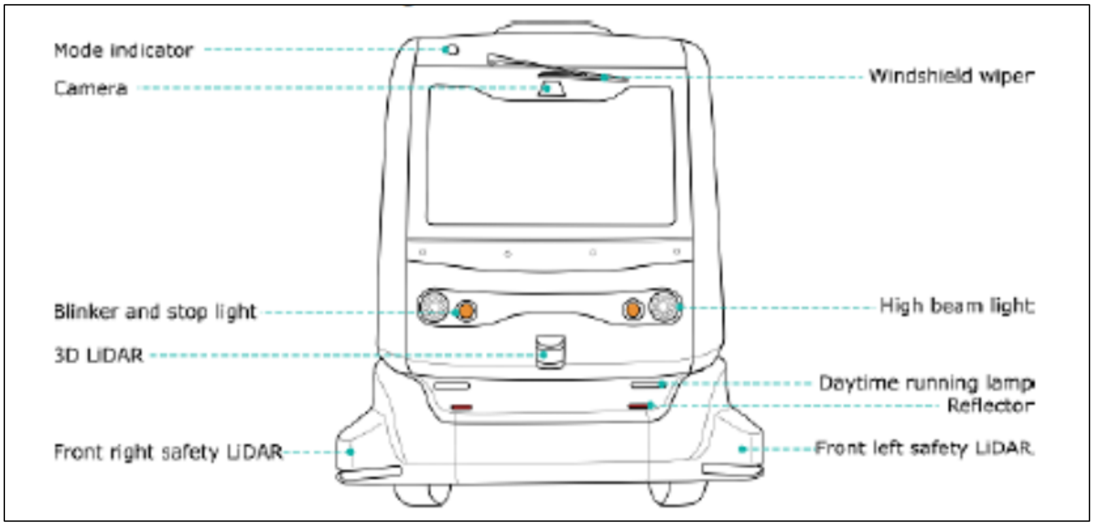

Figure 18. Front View of EasyMile EZ10, Gen 3 (some features slightly upgraded from Gen 2)

Personnel Observations

The AV study team queried the two attendants (operators) of the vehicle, who were First Transit employees, to determine their perspective of vehicle operation, passenger responses and their preparation for the job. They responded to a series of questions. Interestingly, both recommended seat belts for passengers and themselves.[1] Both were very optimistic and complimentary of their time on the vehicle and reflect confidence in their feeling of safety on the vehicle. Table 4 reflects the questions asked of the two attendants, and their responses.

Table 4. Questions and Answers of AV Shuttle Attendant

If there were one thing you could change when operating the AV, what would it be? Attendant 1: I would put a swivel chair with a seat belt for the operator. In fact, I would have a seat belt for every rider and limit the number of passengers from 11 to 8. Attendant 2: I would add seat belts for operators and passengers. I've been on the vehicle for a while and when the AV makes emergency stops both operator and passengers get jerked badly, even when holding on to handrails.
What is your most favorite thing about operating the AV? Attendant 1: The new technology. Being part of this operation while it's still experimental is exciting. The students are fun and usually very nice. Attendant 2: Being at the college and having to explain autonomous mode to new riders. I'm a big fan of technology and working on a self-driving AV is something to talk about. Watching it correct itself, slow down when pedestrians are close, and emergency stop to protect everyone on board and those outside.
What is your least favorite aspect of operating the AV? Attendant 1: Operation during the rain. Sometimes the shuttle operates fine, other times you'll have to put it up if it rains too hard. Attendant 2: I don't have a least favorite aspect. To be truthful I actually love this project. Having this experience of operating a self-driving AV was amazing since I've been here.
What works really well during AV operation? Attendant 1: The electronic stops work very well. The sensors will pick up objects near or far and slow down/stop accordingly.

[1] This seat belt addition is required by NHTSA as a result of the vehicle's emergency stop that occurred in Columbus, OH.

Attendant 2: The AV safety sensors and breaks. Working this project, I've seen a lot of people walking closely to the AV and completely cutting it off. Every time that happens the shuttle quickly emergency stops so it wouldn't hit that person. It can even pick up a small leaf flying in front of the sensor and emergency stop. That's how well this system works.
What skills would have better prepared you for this job? Attendant 1: Other than maybe having a little more skill as a mechanic, nothing. Nothing can prepare you for a position like this, because there's no other jobs out there like this, yet. You just must be a people person, be patient and be able to stand on your feet for long periods of time. Attendant 2: I don't think it's any skill that could've better prepared me for this job. I also think training for this job was amazing and with me being coachable and wanting to learn more truly prepared me for this job.
How safe do you feel operating the AV? Attendant 1: Very safe. From my time operating the shuttle, I never felt at any time I was in any danger while working. Attendant 2: I feel extremely safe operating the AV due to the safety chain and sensors. Being able to detect obstacles, adjust speed on its own and break when people or things are to close. The AV protects everyone inside just as well on the outside.
How safe do you think the riders felt on the AV? Attendant 1: I've talked to some students about this and they've all said they felt safer on the AV shuttle than the manned ones simply because it goes a little bit slower and doesn't dart around the Tiger Walk trying to go around people. Attendant 2: I think the riders felt extremely safe. I've had conversations with some riders who wanted to know why it slowed down by itself and emergency brakes. Once I explain it to them, they ride more.

Battery Operation

Battery life, which can be expressed in terms such as the operational range of the vehicle on a single charge or its rate of depletion, is a major point of attention throughout the AV transit industry. This area of research is one of the key focal areas for the TSU AV project. METRO and TSU were approached with a proposal for a collaborative research endeavor by the Idaho National Laboratory[2] (INL), a Department of Energy (DOE) laboratory, to assess the battery utilization of the vehicle. Three approaches were pursued and are presented below for assessment. First, the work by INL, which reflected readings from their equipment. Second, daily temperature, rain and humidity recordings by the on-campus operations team, as well as instances when the vehicle was removed from service because the battery was nearing the 20% charge level.[3] Third, a demonstration of several scenarios was enacted in August 2019.

[2] Mr. Matt Shirk of the Idaho National Laboratory leads the Energy Consumption research at INL under the DOE SMART Mobility Research program.

[3] A battery charge level of 20% is the lowest percentage at which the vehicle can operate properly based on manufacturer specifications. Whenever battery charge approached this level, attendants removed the vehicle from service and returned it to the maintenance area for re-charging.

Idaho National Laboratory Assessment

The Idaho National Laboratory (INL) offered to include TSU's AV project in an assessment of battery endurance the agency was concurrently conducting for several US automated vehicle projects. The INL installed a meter in the Central Storage facility that compiled readings when the vehicle recharged.

Idaho National Laboratory (INL) Power Consumption Data Collection Equipment: The power consumption research by INL was accomplished using a special meter which was installed between the vehicle charging plug-in receptacle and the breaker panel, as shown in Figure 19. Their equipment monitored and recorded the charging power 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 these data the energy consumed during the vehicle operations was studied. 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.

Figure 19. Arrangement of INL Power Consumption Monitoring and Data Transmission Equipment
Source: Matt Shirk, Idaho National Laboratory

Power Consumption Research Results: The INL partnered with Houston METRO and Texas Southern University to compile the daily field data collected from the TSU Shuttle operations. The research was performed under the auspices of the DOE Vehicle Technologies Office SMART Mobility research program. Each day a log was kept of odometer readings as well as the battery state-of-charge (SOC) in the vehicle before it was placed in passenger service on Tiger Walk. Also, raw energy consumption data were transmitted directly to INL by the data logger equipment located in the TSU shuttle maintenance and storage bay. The data collection was a coordinated effort between METRO, TSU and the Contractor project team, with the recorded operational data being periodically sent from Houston to the INL researcher. The researcher then compiled the desired energy intensity values received from the Houston AV Shuttle operations with the raw energy consumption data transmitted directly by the data logger equipment. Figure 20 illustrates how the data components for battery charge and vehicle operation were recorded, assembled and checked for quality assurance, using data collected between June 10 and June 12 as examples.

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

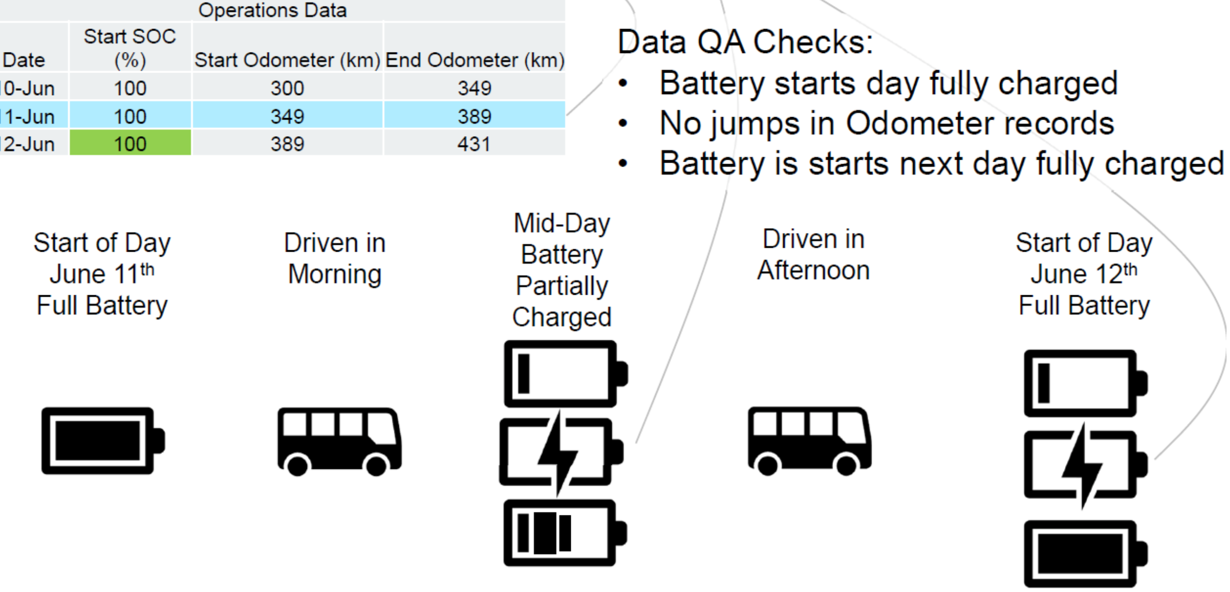

Figure 20. Assembly of Data
Source: Matt Shirk, Idaho National Laboratory

In addition, INL investigated the ambient temperature for 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. These recordings resulted in a rich database of power consumption as a function of vehicle-miles travelled and ambient climatological conditions while the vehicle was in service between June 10th and November 20th, 2019. The complete set of data and associated operational information was a joint effort of INL researchers with the supporting participation of TSU researchers, First Transit operations staff, and EasyMile engineering staff.

Figure 21 illustrates the vehicle's energy consumption as a function of the average vehicle speed. The primary metric derived from the compiled data is designated as the energy intensity, with units of watt-hours per mile. The two boundary areas identified in the figure by solid lines show the research conclusions for the range of energy consumption for both a slow speed AV shuttle (5 mph average speed) and a higher speed AV shuttle (10 mph average speed). As can be seen in the figure, the data cluster for the TSU operations provided the results for the 5 mph average speed. INL also collected data from two other university demonstration projects which reflect the 10.7 mph average speed results. These are important findings of the INL research concerning energy consumption forecasts for future AV transit applications. The figure also tracks the energy consumption effects of seasonal weather on non-tractive loads, primarily accessories like heating and air conditioning. The data points are the compiled record of the average speed during a given day's operating hours (including time stopped at boarding locations) and the distance the vehicle travelled.

The acronyms and nomenclature used in the figure 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)
- kW acc. load – kilowatt energy consumed by accessory equipment loads (non-tractive)

Further information about how information was recorded and processed by the INL, as well as a summary of their findings, is provided in **Appendix C**.

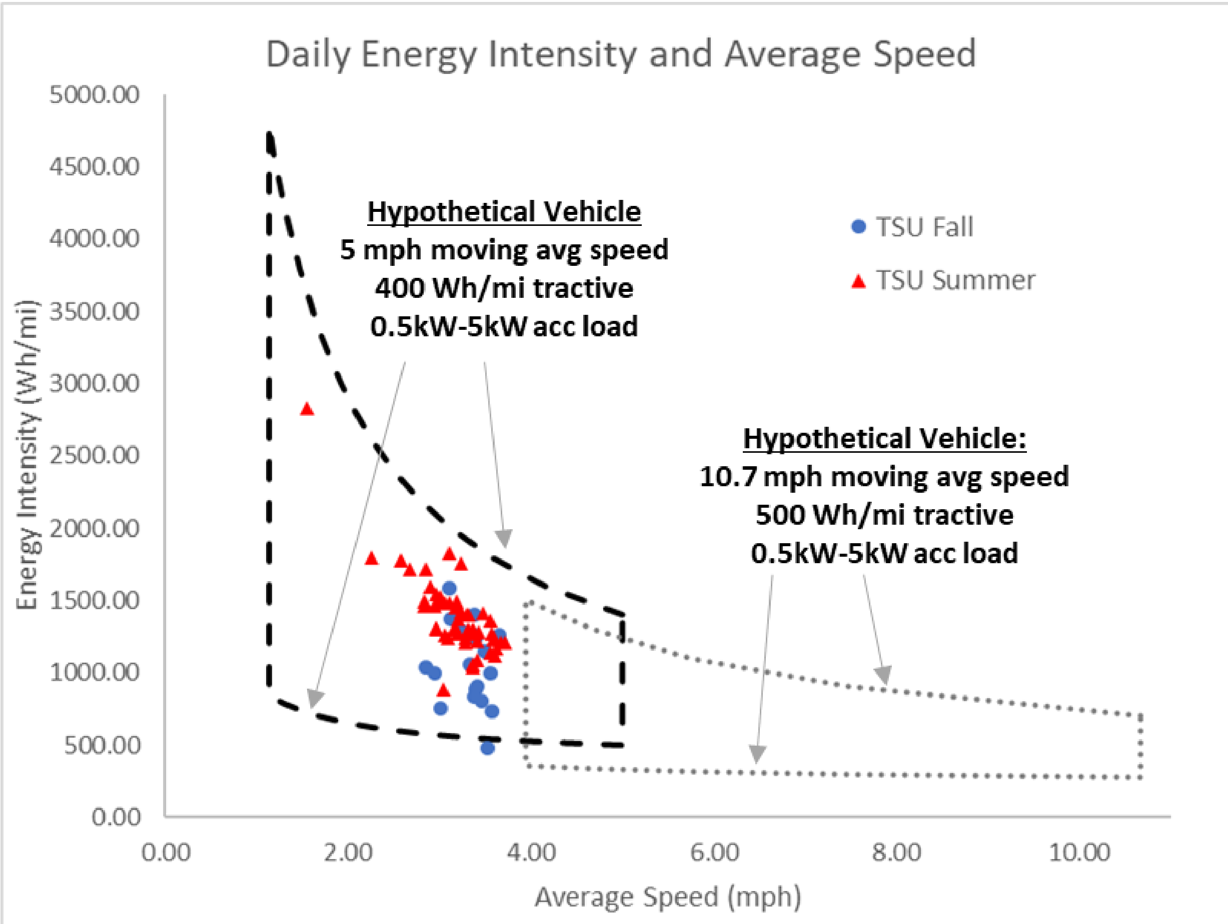

Figure 21. Energy Consumption Data as a Function of Average Speed and Seasonal Climate Impacts
Source: Matt Shirk, Idaho National Laboratory

The INL research greatly benefited from the high-quality data provided by the TSU AV Shuttle's extensive operational records.

TSU Field Review

The on-campus operations team recorded rain totals, humidity, temperature and battery utilization. Also noted were days the vehicle was pulled because the battery neared the 20% charge level (on occasion to complete the run, attendants allowed the battery to decline to 17%, but never lower). During the month of July, the vehicle was pulled 9 of 21 days due to the battery nearing the 20% level.

Figure 22 shows the percent battery utilization during a selected period during the height of summer compared to temperature and the percentage of battery utilization. Of note is that the battery percentages tend to hover around 80% as the temperature is 90 degrees or higher. The exception is August 15 and for which there is no apparent rationale. The AV's air conditioner has two settings, low and high. Ridership was modest during July and August, so the air conditioner was generally set on low. On temperate days, the attendants ran the vehicle without the air conditioner. During the end of October, Houston had two mornings in the low 30s. Ridership was high those days and attendants used the heater. Still, the battery level did not fall below 33%.

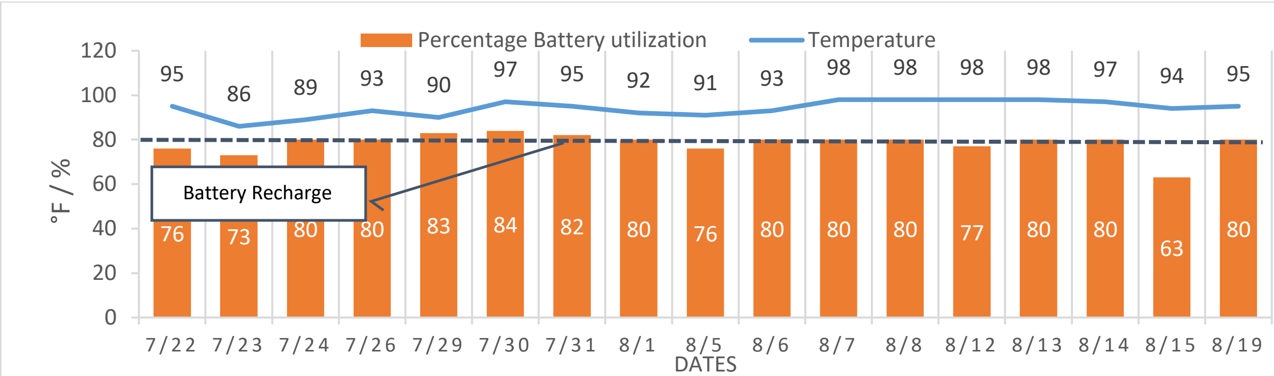

Figure 22. Percent Battery Utilization and Temperature (Degrees Fahrenheit)

The summer months of July and August have the highest average monthly temperatures in Houston (the average temperature for July and August is 93 degrees F; by September that declines slightly to 89 degrees Fahrenheit) and provide information necessary to understand the battery duration in these temperatures. Average humidity was also recorded; however , humidity was determined not to have a significant effect on battery life. Table 5 shows Houston's official weather recordings (as reported by the Weather Underground website) for a selected set of days in July and August corresponding with the time period depicted in Figure 22 above:

Table 5. Humidity, Temperature and Battery Levels

Date	Inches of Rain	Average Humidity	High Temperature	Battery Level at Time of Recharging
7/22/2019	0	75%	90	24
7/23/2019	0	71%	89	27
7/24/2019	Trace	48%	89	20
7/26/2019	0	58%	93	20
7/29/2019	0	68%	94	17
7/31/2019	0	73%	93	18
8/1/2019	Trace	67%	94	20

8/2/2019	0	65%	97	20
8/5/2019	Trace	71%	91	24
8/6/2019	0	70%	94	20
8/7/2019	0	69%	96	20
8/8/2019	0	67%	98	20
8/9/2019	0	67%	98	20
8/12/2019	0	67%	99	23
8/13/2019	0	66%	98	20
8/14/2019	0	74%	99	20
8/15/2019	1.9 in	70%	94	37
8/19/2019	Trace	77%	96	20

Source: https://www.wunderground.com/history/monthly/us/tx/houston/KHOU

The vehicle cannot operate if a steady rain begins, as the sensor logs intense rain as an obstacle and the vehicle slows down or stops. Therefore, if the attendant begins to experience a slow-down due to rain, the vehicle is pulled into the storage location. During the 8 months of shuttle demonstration, there were fewer than 7 days when the vehicle was pulled due to rain. If the rain ended with sufficient time to complete the run, the vehicle was reengaged.

Battery Utilization Test (August 2019)

There are four USB ports in the vehicle for charging personal devices such as smartphones. The team discovered that the vehicle's battery was greatly depleted when the charging ports were used by riders. However, it was difficult to determine whether this depletion was caused mainly by device charging, or if the high temperatures, the air conditioning system, and/or ramp deployment for boarding a passenger with a disability were the key factors. Since ridership would be down the week summer school ended but prior to beginning of fall semester, a week of scenario testing was undertaken. The variables for the scenarios were low or high level of air conditioning, the use of the charging portals, and engagement of the ramp (Table 6).

Table 6. Scenarios Tested for Effect on the Battery Level

Day	A/C Level	Device Charging	Hours of Operation	Number of Ramp Deployments
Monday	High	Yes	8am – 2.30pm, 5pm-7pm	4
Tuesday	High	No	8am – 2.30pm	4
Wednesday	Low	Yes	8am – 2.30pm	4
Thursday	Low	No	8am – 2.30pm	4
Friday	Low (morning) and High (afternoon)	Yes	8am – 2.30pm	4

During this week, the vehicle's attendants noted the battery percentage at the start and end of operation. The ramp on the vehicle was deployed twice in the morning and evening to fulfill the four times of deployment required each day. According to the scenario of the day, the operators either encouraged or discouraged phone charging by passengers. Temperatures during this week ranged between 82 degrees and 99 degrees. These temperatures were regarded as relatively high and focus was put on the air conditioning level (low or high) and phone charging.

As observed in Figure 23, the rate of depletion of the battery at a high A/C level was higher with phone charging than without phone charging. On both Monday and Tuesday of that week, the vehicle was withdrawn at 1:30 p.m. - an hour before its scheduled end of operation - to recharge so it could resume operation at 5 p.m. as scheduled. So, it is worthwhile to note that when the A/C level was high, the vehicle was unable to complete the scheduled hours of operation on a single charge due to high rate of battery depletion, especially with phone charging.

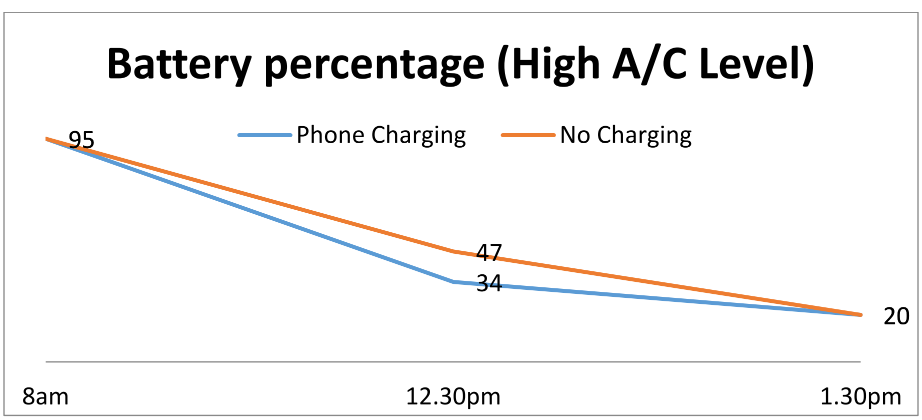

Figure 23. Scenario High Air Conditioning

Figure 24 shows that the battery charge depletes at a lower rate with a low A/C level compared to that of a high A/C level. At a low A/C level, the vehicle was able to fully operate the scheduled hours of service. With no device charging, the vehicle completed operation at 37 percent charge, which is sufficiently above the manufacturer-recommended 20 percent charge for vehicle withdrawal.

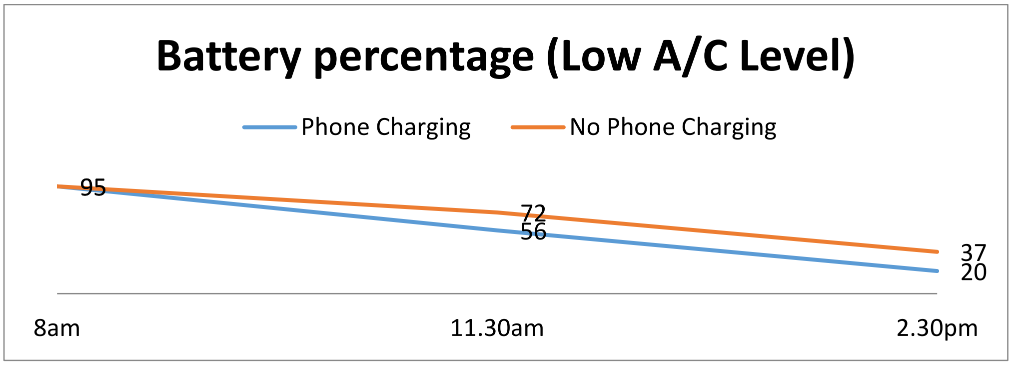

Figure 24. Scenario Low Air Conditioning

Although many elements may contribute to the vehicle's battery depletion, it is worthwhile to note, based on these results, that A/C level and phone charging have a significant effect on the depletion rate of the battery.

Daily Operation and Scheduled and Unscheduled Service Disruptions

The TSU AV's daily operation followed a schedule established based on the campus population for the semester as well as peak volume expectations, such as the end of class or lunch time. For instance, in July, service operated from 8 a.m. until the battery charge level showed 20%, usually between 3:15 p.m. and 4 p.m. This decision accommodated the low volume of activity on campus during summer evenings. Beginning with the fall semester on August 26, 2019, the shuttle operated from 8 a.m. to 2 p.m. with a break to recharge the battery and change attendants. Service resumed from 5:00 p.m. to 8:00 p.m. Classes ended for the fall semester on December 13 and began again on January 27 for the spring semester with the same operating schedule as in the fall.

Before the start of every shift, the attendants performed a visual inspection of the vehicle and a test drive to ensure proper functioning of the vehicle's computer and mechanical systems. During the visual inspection, attendants inspected the vehicle's LiDARs, tire pressure, and cleanliness. While performing the test run, the attendants ensured that the fusion uncertainty (multiple sources that ensure data integrity) and localization were functioning correctly.

For the fall semester, the shuttle usually operated as scheduled, but experienced occasional disruptions by various events and incidents. These included inclement weather, mechanical issues, software malfunctions, campus events, and other miscellaneous incidents (Table 7).

The schedule was adjusted to accommodate specific campus events if those occurrences were known in advance. The AV team retrieved events from calendars of different schools, departments and the TSU Events Manager. Nevertheless, some events during the fall semester caught the team off-guard and the vehicle schedule was altered sporadically and in an unplanned manner. Furthermore, unpredictable occurrences like weather, mechanical issues and software malfunctions abruptly caused alterations in scheduled service.

Table 7. Events Causing Service Disruption During Fall Semester

- August 18th Service was shut down from10am to 11:30am due to workers working on the fountain.
- August 26 – Staged for First day of School
- August 28 – Operation stopped due to Pep Rally at 12 p.m.
- September 10 – Democratic Debate setup
- September 18 – Heavy Rain
- October 1 – Police activity (Bar-b-que)
- October 2 – Police activity (Lattes with Law Enforcement on the Tiger Walk)
- October 3 - Special event
- October 9 – Preliminary Homecoming
- October 17 - Hump Day activities
- October 24 – Homecoming
- November 7 - Gospel Concert
- November 28 & 29 – Thanksgiving Holiday

After the winter break, the decision was made to learn of events in advance to schedule and log the events for the spring semester and plan for AV service modifications. Table 8 shows events and incidents that disrupted daily operation and caused the shuttle's daily schedule to be altered during the 2020 spring semester.

Table 8. Service Disruption Events Spring Semester, January – February, 2020

Month	Week	Event/Incident	Date	Disruption Details
January	3	MLK Day	1/20	School Closed. No shuttle operations
		Rained all day	1/22	No shuttle operation

		Power outage	1/24	School Closed. No shuttle operations
	4	Multiple 18-wheelers on Tiger Walk	1/27	18-wheelers were transporting generators utilized to stabilize the power system on campus away from the buildings. Shuttle operations were halted a little after 6pm.
		Vehicle tilted	1/27	Shuttle was tilting to the side while moving. EasyMile technicians and the operator fixed the shuttle and it resumed operations at 5pm.
February	1	Removal of generators from campus buildings	2/5	Shuttle operations had to be halted for the campus police to coordinate the removal of generators from various campus buildings. The shuttle was expected to resume operations after the incident.
		Refueling of generators	2/10	Shuttle operations had to be momentarily halted due to refueling of generators along the Tiger Walk.
	2	Software malfunction	2/11	Shuttle's GPS system was unable to connect or localize. After numerous attempts to troubleshoot the system, the shuttle was withdrawn from operation at 3:30pm.
		Software malfunction	2/12	The shuttle was out of service because the previous day's GPS system malfunction was being fixed .
		Routine maintenance	2/13	The shuttle was scheduled for routine maintenance. It was already withdrawn from operation due to previous software malfunction problem.
	3	CV Joint repair	2/13	Discovered during routine maintenance. The parts needed for the repair had to be shipped from France and took longer than expected causing the shuttle to be out of service for most of the week (2/17 – 2/20). The shuttle resumed operation Friday afternoon (2/21)
		Rain	2/24	Shuttle started operating at 9am instead of 8am due to rain
	4	Operational shutdown of all	2/25	Following an accident that occurred on board an EasyMile AV in Columbus, Ohio, EasyMile

		EasyMile AVs, as required by NHTSA		suspended all autonomous shuttles operating in the U.S. Operation of the shuttle is pending a press release from NHTSA.

Of the eleven incidents that happened during the spring semester, four were unexpected campus incidents, two were mechanical malfunctions, two were rainfall occurrences, one was a software malfunction, and the rest were miscellaneous incidents. The last incident on February 25 did not happen on the TSU campus but nevertheless caused indefinite halting of operations of all EasyMile vehicles nationwide until NHTSA authorized reengagement. As EasyMile prepared its response to NHTSA, however, the COVID-19 pandemic consumed the United States, with TSU issuing a work from home and distance learning mandate. Seat belts and other improvements will be added to the vehicle readying the service to begin once campus is reopened.

Coping with Schedule Disruptions: It proved difficult to predict the duration of any incident, and therefore made it hard to predict how operations would be affected for the rest of the day or week. Therefore, coping and managing disruption in the shuttle operation required effective communication between the university, maintenance operation managers, the shuttle attendants, the project lead, and campus police. Service adjustments were more easily accomplished if the cause of event was known in advance. When campus events were known in advance, the shuttle's schedule was easily altered or halted for a period of time to accommodate that particular event.

While weather forecasts were consulted prior to daily vehicle operations, the response to weather was largely left to decision making by the attendants. Operations depended on the severity of the rain, which was not always predictable in advance. The shuttle operated in light rain, but slowed or stalled when the rain became heavier and needed to be removed from service. Unanticipated service modifications required coordination with campus police, potentially EasyMile technicians, and communication with the project lead to convey the time and reason for ending or modifying the shuttle's operation. Depending on the incident and duration, the project lead and shuttle attendants determined when service would resume.

Vehicle Maintenance and Incidents

The attendants recorded anomalies in operation each day. These included vehicle malfunctions and emergency stops. Malfunctions in the vehicle ranged from software glitches that could be addressed from EasyMile's Denver office to matters that required vehicle transport to First Transit facilities for more extensive repairs. The vehicle required maintenance that removed it from the TSU campus twice: November 13 to 15, due an on-board diagnostic and a wheel failure, and December 5 to 9, for software repairs. Beyond the vehicle repairs, two emergency stops (e-stops) were reported, one from a student walking in front of the vehicle and once from a student on a skateboard. Additionally, attendants operated in manual (not automated) mode for several days at the end of system loop at the Spearman Technology Building, because grass height was interfering with vehicle sensors. Software malfunctions included inability to read mileage, issues related to audio speakers, odometer error, and diagnostic testing. These maintenance events indicated that having only one vehicle in service, with no spare, was not an ideal operation.

Stakeholder and Community Engagement

Several planned events sponsored by METRO and TSU marketed and promoted the AV project. In June 2019, the project held events for the media and elected officials and the public. The project team also hosted a University Transportation Center meeting on June 7, 2019, showcasing the AV. Throughout the summer, METRO offered AV tours each Friday to groups and interested stakeholders. TSU faculty conducting youth summer programs also offered tours for participants. On September 8, METRO also sponsored the *Automated Vehicle Workshop*, an event which drew transportation professionals from various Texas cities to ride the AV as well as motorized scooters and bicycles. Throughout the Fall 2019 semester, former TSU President Austin Lane held "Chat and Cruise" events where students rode the AV and asked the President questions. Finally, in December 2019, the AV was transported to and staged at NRG Stadium for a Houston Texans football game. Before the game, the public received information about the AV and were invited in to see the shuttle.

AV Survey Results: Feedback was received from students, faculty and visitors who rode the vehicle and completed a consent form required for research protocol. By way of the consent form, riders agreed to participate in the AV demonstration project, confirmed they were 18 years old or older, and took the AV survey. Completion of the survey instrument generated 1357 responses from the 2925 persons 18 years old and over who received a consent form. Forty-six (46) percent of all riders provided input. Some surveys had unanswered questions in situations where the riders failed to fully complete the survey. The responses to some of the questions asked in the survey are discussed below and shown in Tables 9 through 3.

Per Table 9, 362 riders knew nothing about automated vehicles, while 587 riders stated that they knew *a little* about the vehicles; 270 riders answered that they knew *much*. The percentage of people knowing nothing (10%) was comparable to the percentage who knew much (12%).

When asked where they had learned about automated vehicles, more than 250 riders responded that they learned from class or from academic readings. Most riders (33%) learned of AV through the internet or a blog. This response is not unexpected since most students rely on their phones and social media for communication. Other riders indicated they learned about the AV from news or TV.

Riders were asked what they thought about sharing the Tiger Walk with a driverless vehicle, roughly the size of a large van. Some respondents had no opinion, while a few noted a bit of nervousness about the vehicle. However, 73% answered they have no problem sharing the Tiger Walk with the AV. More than half of the AV's riders responded they are between the ages of 18 and 24. The second highest category were 25-to-34-year-olds, at 12%.

Table 9. How much have you heard about the driverless vehicle?

Nothing	362	27%
A Little	587	43%
Much	270	20%
No Response	135	10%
Total	1357	

Table 10. What has been the source of your information?

In-class/ Scholarly	258	19%
Internet/ Blog	445	33%
News-TV/Newspaper	114	21%
Conversation with Others	368	12%
No Response	168	12%
Total	1357	

Table 11. What do you think about sharing the Tiger Walk with a driver-less vehicle about the size of a large van?

I have no opinion	113	8%
It makes me a bit nervous	66	5%
It's fine; no problem	997	73%
No Response	181	13%
Total	1357	

Table 12. How do you feel about sharing the Tiger Walk with an AV?

Don't Care	1	0%
No - would rather walk	74	5%
No- Fear, don't trust it	74	5%
Yes - reluctantly	443	33%
Yes - Would be excited	565	42%

Other	8	1
No Response	189	14%
Total	1351	

Table 13. Age of Respondents

18-24 years old	725	53%
25-34 years old	169	12%
35-44 years old	56	4%
45-54 years old	44	3%
55-64 years old	22	2%
65-74 years old	7	1%
No Response	333	25%
Total	1356	

Miscellaneous Lessons Learned

The AV shuttle program provided many avenues for learning about vehicle characteristics, passenger acceptance, battery duration and operation. In addition, important unanticipated concepts emerged that will inform and enhance future service opportunities.

Discoloration along geocoded route: Several months into the TSU demonstration, EasyMile informed the project team that the Gen 2 AV eroded or discolored pavers along its geocoded route at other pilot program sites. This effect was only observed once at TSU when the grounds staff power washed the Tiger Walk; after 24 hours, the discoloration was no longer visible. The erosion was caused by the vehicle's tires rolling repetitively along the same route. EasyMile suggested that slight deviations be programmed into the route to prevent “wear and tear” of pavers or streets. This should be done as additional vehicles are added to the demonstration to alleviate problems.

Improving Passenger Information: METRO operates a systemwide GPS tracking system to inform riders of arrival times of their buses and trains. However, integrating the AV into METRO’s notification system did not occur because it would have required installing additional equipment, and EasyMile did not allow any modifications to the vehicle. Throughout the AV demonstration, service interruptions occurred due to weather, major campus events, or vehicle maintenance. During these times, the project team was unable to broadcast messages about service limits or cessation via TSU announcements or METRO’s system. Instead, the project team placed “Out of Service” placards at each shuttle stop (Figure 25). Phase II of the AV demonstration will involve up to three vehicles and will operate an extensive route. As Phase II begins, an automated notification system must be employed to provide predictability of service for riders at TSU and the University of Houston (UH).

Figure 25. Manually-Displayed Sign

Operations and Maintenance Cost Estimates

Capital and operation and maintenance cost estimates for AV shuttle operation are included for informational and discussion purposes. A myriad of options could be explored; four are shown here that demonstrate the progressive relationship between costs and carrying capacity. selected case options (Table 14), which are explained in more detail in **Appendix B**, reflect a range of vehicle sizes, operating speeds, fleet sizes, headways and carrying capacity from smallest to largest. Option 1 has the lowest operating speed of 12 mph and the remaining options increase to 20 mph. Options 1, 7 and 11 have 6 seats, but option 12 examines a larger vehicle seating 12. The remaining columns presume the number of vehicles available for operation (In-Service Operating Fleet), how frequently a user could access a vehicle (Average Headway), and the number of people (people per hour per direction – pphpd) that could be accommodated (Route Hourly Throughput Capacity).

Table 14. Case Study Modeling Results for System Operational Performance Metrics

Case Study[1]	Maximum Operating Speed (mph)	Vehicle Passenger Capacity	In-Service Operating Fleet (Veh.)	Average Headway (Min.)	Route Hourly Throughput Capacity (pphpd)
#1	12	6	3	4.56	79
#7	20	6	5	2.42	149
#11	20	6	8	1.51	238
#12	20	12	4	3.02	238

1. Refer to Appendix B for all case studies and additional explanation

The tables show the two vehicle capacity limits of 6 passengers and 12 passengers that were postulated as the maximum to be allowed in the vehicle when operating in mixed traffic conditions. This analysis is very relevant to issues now being actively considered by NHTSA. Indications are that they will allow no more than 6 passengers on the EasyMile vehicles when operating in mixed traffic and all six passengers will have seatbelts provided for their safety. It is likely that additional safety design and testing will be required to prove the vehicle's safe operation before the vehicles will be allowed to operate while passengers are standing in the vehicle. The case studies with 12 passenger vehicle capacity are insightful for a future time when either a larger vehicle is deployed, or when the safety of the smaller EasyMile vehicle has been sufficiently proven in mixed traffic operations such that seated-passenger-only restrictions have been relaxed by NHTSA.

Capital Costs

Calculation of capital cost begins with the leasing cost of the vehicle and the recognition that U.S. agencies typically have chosen to lease, as opposed to purchase, AVs to-date. Operator/attendant salaries, vehicle charging time, and the design requirements for support facilities all have a direct bearing on the cost of the total fleet size and electrical charging infrastructure. Table 15 presents the capital/project cost estimates, which are substantially affected by the total fleet size of each given case study. 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.

There are two points of emphasis concerning these costs: first, that they are the cost for a complete operational system, and second, that there is an incremental additional cost for system capacity expansion once it is completed. The component costs of the total were analyzed in accord with the following breakdown:

- Transitway/Roadway
- Vehicles
- ITS/System Automated Control Infrastructure
- Communications Systems/Equipment
- Battery Charging Power Supply and Equipment
- Station Equipment
- Maintenance Area Provisions
- Spare Parts and Supplies
- Intangible Project Support
- Contingency

Table 15. Capital Cost Estimates for Selected Case Studies When Procured as a Whole System

Case Study[1]	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

1. Refer to Appendix B for all case studies and additional explanation

Operation and maintenance (O&M) cost estimates were developed for a selected subset of operational case studies for capital costs, and are presented in the Table 16 in summary form. The estimation of operations and maintenance costs for a fully automated AV transit system can at this point in time 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. Development of the cost estimates was accomplished using the cost categories of Payroll, Maintenance, Energy and Vehicle Fleet Depreciation.

It is important to understand that even though an AV transit technology is operating along public roads with unmanned vehicles, it does not mean that there is no need for substantive staff supporting the system operations. Full automation will allow for operations staff to manage and support a fleet of vehicles that are being dispatched automatically in real time by the supervisory system in response to dynamic changes to travel demand patterns.

To assist in the comparisons between case studies in the table, similar vehicle-fleet parameters are included in the O&M cost summary table as used in the Capital Cost Summary table above, with the addition of the daily vehicle-miles traveled for the fleet.

Table 16. Operations and Maintenance Cost Estimates for Selected Case Studies

Case Study[1]	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

1. Refer to Appendix B for all case studies and additional explanation

Observations from the Cost Estimates

The variables explored in this section are the primary drivers of the capital/project costs and the operations and maintenance (O&M) costs for a range of AV operational options. Time will give a better basis of the probable capital and O&M costs to be anticipated as actual AV transit system deployments are undertaken in increasing numbers of deployments around the US.

Summary Findings

The AV team learned much from the TSU shuttle demonstration project. There were three primary purposes of the TSU AV pilot project:

- Gain insight into the operational characteristics of the AV during fair and inclement weather,
- Acquire knowledge of battery capabilities during temperature variations, and
- Assess perspectives of riders and vehicle attendants (the term attendant is intentional to show variation in task requirements in contrast to a METRO Operator).

The vehicle performance was fine during fair weather and in light rain; however, it was unable to maintain operation during a heavy rain.

Battery life is an important consideration, especially in climates with extremely warm summers such as Houston. Hot weather, engaging the air conditioner or heater and use of USB ports definitely impacted battery life. This project had a short route, but the vehicle required discontinuation of service for almost half of the days in July before the scheduled run time ended. The team learned that the vehicle interior generally feels comfortable with the air conditioner on the lowest setting, which does extend the battery duration. It is, however, worth noting that riding on the Tiger Walk is short, generally less than 12 minutes. A longer time on the vehicle with a crush capacity might not be comfortable with the air conditioner on the lower setting.

Acceptance from the student, faculty and staff and visitor populations were enthusiastic and people were generally not intimidated by the automated nature of the vehicle. Mostly riders enjoyed and accepted the vehicle without reservation. The attendants reported a high level of satisfaction with operating the vehicle and with the position of attendant.

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