RESEARCH & DEVELOPMENT

Feasibility and Demonstration of Small Automated Vehicles as a Viable Transit Solution in NC

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Abstract:

This report explains the findings from "Feasibility and Demonstration of Small Automated Vehicles as a Viable Transit Solution in NC," the first phase of multi-year project developing the EcoPRT system. This system uses two-person, driverless vehicles as part of an autonomous mictrotransit system. The vehicles can bring passengers door to door for short distances at low speeds along shared-use pathways. During this phase, the first two EcoPRT vehicles were built and tested and construction was begun on an additional three. The campus of North Carolina State University was examined to see how best to design routes to increase students' accessibility to desired locations. Potential users (students, staff, and faculty) were given intercept surveys and participated in focus groups; these instruments found a positive reaction to the EcoPRT concept, although concerns remained on safety and, particularly, reliability. Finally, a benefit-cost analysis was performed, which found that the direct benefits would be greater than the direct costs, particularly if the increased mobility brought on by EcoPRT allows the university to avoid building a parking garage on center campus and instead enables travelers to use surface lots on Centennial Campus.

Key Words **Automated vehicle, microtransit, obstacle detection, pedestrian detection, shared mobility**		Distribution Statement	
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Without the help of all the above individuals, as well as many undergraduate and graduate student assistants, the research team would not be able to be complete the project in a successful and timely manner.

Disclosure

As a point of disclosure, during the period in which this contract was performed, two of the authors, Seth Hollar and Marshall Brain, have incorporated a company, EcoPRT Inc. The company licenses technology from NC State University with the purpose of commercializing autonomous vehicles.

Executive Summary

Microtransit systems present a technological solution to the first mile / last mile gap, which involves getting individuals between home and transit stops. Filing this gap can increase the utility of transit as a viable travel mode. The paradox of microtransit is that the vehicles need to be small in order to maximize flexibility, yet smaller vehicles increase the cost to transit operators as more drivers are needed. Advances in automation technology have given rise to *autonomous microtransit* (AMT). AMT vehicles are driverless vehicles that can vary in size and service need; collectively they are scalable to a larger mobility system.

EcoPRT is an AMT system able to transport passengers easily and inexpensively for distances less than 10 miles – examples include university campuses, business parks, shopping malls, military bases, downtown regions, retirement developments, and amusement parks. EcoPRT employs small, driverless vehicles that can take two passengers at slow speeds (10-20 mph) along shared-use paths, providing actual door-to-door service. The vehicles can take students from classroom to classroom, mobility-impaired individuals to grocery stores, and commuters to a bus stop to ride an express bus. Furthermore, EcoPRT can do this at a low-cost, with a simple installation that can be scaled quickly and easily as context dictates.

North Carolina State University (NCSU) is an ideal test bed for EcoPRT. The newly constructed Centennial Campus is located approximately 1.5 miles south of the main campus. The NCSU Wolfline bus system transports passengers between them, but is limited in where it can travel. EcoPRT could augment the existing transit system by greatly expanding the number of access points, potentially reducing the need for expensive Main Campus parking structures.

This report covers four elements of EcoPRT's development and integration into existing systems:

- **EcoPRT Vehicle and System Development:** Engineers and students in Mechanical & Aerospace Engineering, Electrical & Computer Engineering, and other departments have designed, built, and tested two autonomous vehicles with three more under construction. Features of the customized design of the vehicle include drivetrain, automated steering, route guidance, collision avoidance, and independent suspension. A three-phase approach to pilot testing the system at NCSU has been developed. The first phase is underway with the demonstration of automated route following and obstacle avoidance.
- **Feedback of Potential Users:** Focus groups and surveys were conducted with students, staff, and faculty to measure reaction to the EcoPRT concept and to investigate future use. Overall, participants were positive about EcoPRT and wanted to see its implementation. The reliability of the system was the chief concern, followed by safety.
- **Economic Impact/Benefit-Cost Analysis:** The direct costs and benefits creating a system were analyzed. Assuming EcoPRT could allow NCSU to avoid building a large parking structure on center campus and instead utilize new and existing surface lots on Centennial Campus, benefits significantly outweigh the costs. Other monetized benefits were safety and value of time, while non-monetized benefits included environmental sustainability, community mobility, and student livability.
- **NCSU Corridor Feasibility:** Using a novel approach to determine mobility and accessibility, the NCSU campus was mapped to examine where EcoPRT could best be utilized. Mobility and accessibility gaps were found to be most prevalent on Centennial Campus, where the number of destinations accessible to walkers and even bicyclists is extremely limited. An initial corridor extending from Centennial Campus, along South Campus onto Main Campus and Northeast Campus is presented.

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1. Introduction

As traffic volumes across the country continue to grow, roadway capacity and operational abilities are pushed to their limits - particularly in large metropolitan areas. Space and finances are limited in cities, so typical solutions such as road widening and/or building interchanges are less feasible. Raleigh, NC represents illustrates the problem well. The population of the Raleigh metropolitan area is expected to grow by 72% over the next 25 years, requiring substantial plans to be set forth to accommodate the massive traffic increase that will accompany that population boom (Thomas & Mukherjee, 2016).

In addition, there are numerous places in North Carolina where special conditions create an opportunity and need for microtransit systems. College campuses, corporate campuses, large shopping centers, airports, fair grounds, sports complexes, amusement parks, etc., create environments where people need to move distances which are too far to walk while at the same time too short to drive. At North Carolina State University (NCSU), walking from one library to another can be impractical because a 2-mile distance takes approximately 45 minutes on foot. Meanwhile, driving that distance is impractical because of traffic and parking considerations. Existing campus bus systems are also problematic because traffic delays and multiple stops can stretch what should be a 5-minute trip to 20 or even 30 minutes. A dedicated microtransit system may be helpful in solving these micro-distance problems.

EcoPRT, a new transportation modality, has been designed to create low-cost circulator and point-to-point systems. EcoPRT combines small, inexpensive, highly efficient, autonomous electric vehicles with an elevated guideway to provide efficient transit with no stops. Passengers find vehicles waiting for them when they arrive at a station and are then transported to their destinations with no stops.

Exhibit 1: EcoPRT depicted at the Hunt Library on NCSU's Centennial Campus

The key characteristics of EcoPRT include (Hollar *et al.*, 2017):

- *Flexibility*. Vehicles can run on existing paths or on dedicated guideways. Compared to existing solutions that a) rely solely on dedicated guideways or b) rely exclusively on existing infrastructure, EcoPRT is a unique hybrid of the two. As a rubber-tired vehicle, it can be operated on existing concrete roadways as a low-speed automated vehicle, and, as a light-weight vehicle, the cost and load requirements of elevated dedicated roadways is substantially less when compared to other vehicles.
- *Low cost*. Light-weight, small footprint vehicles reduce infrastructure costs. A two-person, fully laden EcoPRT vehicle weighs 1,000 lbs., much lighter than conventional automobiles or other PRT systems. Consequently, elevated guideways when necessary are correspondingly less expensive with guideway estimates at approximately $1 million/mile.
- *Convenience*. Automated vehicles would be on demand, allowing point-to-point travel without stopping, all hailed by a smart phone.
- *Organic growth*. EcoPRT's flexibility allows a system to be installed quickly at low cost (even using a single vehicle). Adding additional vehicles or expanding the routes is still a relatively low cost/short term effort allowing EcoPRT to grow incrementally as demand grows. With faster return-on-investments, private funders can accelerate the pace of expansion allow the system to grow organically where demand exists.

This research helped to accelerate development and deployment of a working at-grade EcoPRT demonstration system on NCSU's campus. In all, this research report discusses the following items:

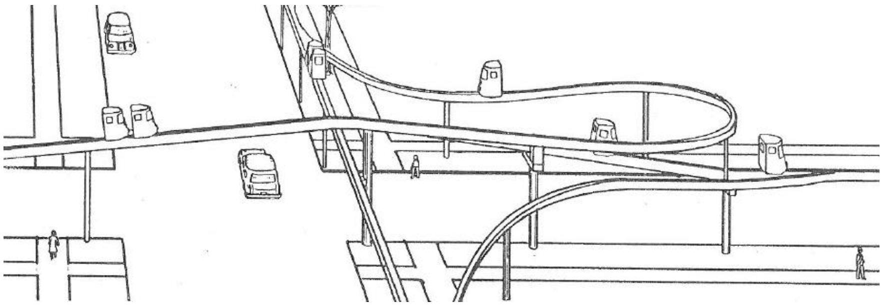
1. EcoPRT Vehicles Operational Performance
2. Corridor Feasibility at NCSU
3. Economic impacts of EcoPRT at NCSU, including potential state-wide impacts for multiple deployments

2. Background

Microtransit has its origin both in the advent of autonomous vehicle technologies and within the personal rapid transit (PRT) community. A good sample overview of PRT literature appears in the report commissioned by the New Jersey Department of Transportation in 2007 (Carnegie, 2007). The concept of PRT dates back as far as the 1950s where Exhibit 2 shows their concept of small, light-weight vehicles on elevated tracks (Northwestern Engineer, 1957). In 1968, the NY State DOT published a concept paper called SCAT: Small Car Automatic Transit (Fichter, 1968). Fichter readily points out the advantages of PRT over conventional systems:

"Development of SCAT technology, however, would permit a breaking away from the tradition of a few specialized, high-capacity transit lines connecting a handful of stations. As a network is made larger there is a rapid increase in the number of places made accessible to one another, suggesting that a large SCAT network may be much more useful in relation to its cost than merely a few routes would be."

Exhibit 2: Drawing of Small Car Automated Transit (SCAT) from 1957



Additionally, there have been a number of feasibility studies performed (Arosa, Switzerland; Cardiff, Wales; Houston, TX; Nottingham, England; Almelo, Holland; Huddinge, Sweden; Ciampino, Italy; Pleasanton, CA; Seattle, WA; Dubai, UAE; San Jose, Santa Cruz, BWI Airport) (Erath *et al.,* 2012). The City of San Jose contracted Aerospace and ARUP to perform a feasibility study for the San Jose Airport (Paige, 2012). Even with a significant cost risk associated with construction, the San Jose study showed that a generic PRT system could be much less expensive than APM or rail solutions. However, Aerospace's report identified uncertainties in both station and guideway capacity (Paige, 2012).

As opposed to PRT solutions with dedicated guideways, Nelessen (1996) proposed "Neighborhood Transit," a network of small buses running on existing roadways that can be dynamically routed real-time. Nelessen argued that current transit solutions which are designed to serve high density corridors performed poorly in suburban dispersed, low density environments where travel cannot be described as a hub and spoke model. Small transit vehicles, on the other hand, can be automatically routed based on current demand, providing a cost competitive, operationally efficient solution. It is interesting to note that 19 years later Uber and other rideshare companies are starting to develop multi-rider solutions that in part implement Nelessen's original Neighborhood Transit concept.

Operational Systems

Early PRT concept papers helped build the momentum when, in the 1970s, Morgantown, WV, received federal funds to build the first operational PRT. Operation started in 1975 and remains the only operational PRT system in the US, still running with over 99% reliability. Some people note that Morgantown's system is not purely PRT, given that vehicles hold up to 21 passengers and can gross 5,400 kg, but rather a "group rapid transit" (GRT) system.

As an anecdote to the history of PRT, in the late 1980's, seeking to commercialize his PRT research, Dr. Anderson from University of Minnesota founded Taxi2000. In the early 1990s, Taxi2000 designs were incorporated into Raytheon's PRT system, dubbed PRT2000. However, the plans deviated from Taxi2000's vehicle and guideway size, roughly doubling the dimensions and tripling gross vehicle weight to 3,000 kg. Due to a number of external factors, a commercial system was never realized. In comparing Morgantown, PRT2000, and Taxi2000, Anderson notes a direct correlation to system cost and vehicle weight:

> *"Estimates of the system costs of the above three systems show that they reduce in proportion to the gross weight of the vehicle – everything scales with vehicle weight."* (Anderson, 2005)

Though guideway-based PRT systems have had some limited success stories, small, low-speed driverless buses on existing road infrastructure are gaining traction. A French company, Induct, has developed a

10-passenger driverless “golf car” that is being piloted at campuses in the United Kingdom, Switzerland, and Singapore. Recently, there has been announcement of another driverless bus, the EZ10, from Easy Mile. The EZ10, also holding about 10 people, is slated to start service in San Ramon, CA, in 2016. Navya and Local Motors also both have autonomous shuttle solutions that are also have a number of on-going pilot projects.

Autonomous microtransit like EcoPRT has the potential to enhance mobility and reduce travel costs for individuals and improve connectivity to nearby destinations and public transportation systems for all households, including low-income and mobility-disadvantaged (Ohnemus and Perl, 2016; Khau, 2013). This project is designed to be repeatable across communities and intentional in designing embedded feedback loops, such that community and user needs and perspectives are reflected in systems engineering design.

CAV and microtransit solutions have traditionally been applied in the public realm by private actors instead of being developed and deployed according to community mobility needs and real travel patterns (Westervelt *et al.*, 2018; Luettle, *et al.*, 2012; Fillen-yeh, 2017). The results are often imprecise and inefficient, such as previous microtransit pilot efforts and, more recently, bike sharing solutions that have had spotty success (Tchebotarev, 2017).

Autonomous MicroTransit in a Campus Setting

University campuses present unique challenges for transportation planning, although many of the lessons learned can be applied to other “campus”-type settings. While travel at a regional level is associated with socioeconomic factors, land use, and travel demands (Ewing and Cervero, 2001), campus travel is dictated by the needs of students and staff, with often significant differences from the general population across trip type, purpose, distance, duration and mode choice (Huegy, 2015). Transportation needs vary throughout the day and often change throughout the week and from semester to semester (Eom, *et al.*, 2009).

Several studies have investigated the relationship between campus travel and spatial-economic factors. Results from Eom *et al*. (2009) and Soria *et al*. (2017) show that statistical correlation exists between travel distance and spatial location, socio-economics and social behavior (“3S”). However, these conclusions are likely unique to the study regions and not generalizable to other places. Furthermore, campus mobility and accessibility gaps are not solely related to the “3S” model. Other factors, like time, travel mode options and cost would also help to explain the problem.

Past research has shown the availability of multiple travel options on a university campus can, in many cases, lead to long-term shifts in how students, faculty, staff, and visitors travel to and from a university campus from locations elsewhere (Balsas, 2003). Specifically, students may influence each other’s mode choices, such as the presence of bicyclists leading to more bicyclists (Wang, *et al.*, 2015). These long-term shifts in travel behavior are more complex, and therefore, much more difficult to model given the level of uncertainty associated with this project. This study attempts to use these considerations, as part of the benefit-cost analysis and corridor feasibility analysis below.

3. The Vehicle

Compared to existing solutions that a) rely solely on dedicated guideways, or b) rely exclusively on existing infrastructure, EcoPRT is a unique hybrid of the two. The vehicles are being designed to work both on dedicated guideways and existing pathways. As a rubber-tired vehicle, EcoPRT vehicles can operate on existing concrete roadways as a low-speed automated vehicle, and, as a light-weight vehicle, the cost of elevated dedicated roadways is substantially less when compared to those serving other vehicles.

We identified weight as a key factor in design. A two-person, fully laden EcoPRT vehicle weighing 1,000 pounds is much lighter than a 12-person vehicle weighing 6,000 lbs. EcoPRT therefore offers cost savings through a reduction in overall infrastructure requirements. Two separate estimates from structural and civil engineering design entities have put the elevated guideway cost around $1 million/mile (estimates available upon request).

The pilot demonstration on NCSU campus seeks to demonstrate the use of the vehicles on existing pathways as the first step in demonstrating the feasibility of the system.

This chapter first discusses the manufacture of the vehicle itself, during the course of EcoPRT Phase I. It will then discuss the control technology and the development of the sensor array, before discussing the testing of the different aspects of the vehicle, including autonomous control.

Exhibit 3: First Prototype Vehicle and Test Track (Before Project Start)

3.1. Vehicle Manufacture

The construction of these initial EcoPRT vehicles have involved a series of tests between each iteration, in order to build off lessons learned from each model. Primary construction tasks on each of the vehicles included creating the welded frame for the vehicle, adding drivetrain components, adding suspension, components, adding steering components, adding brake components, adding wheels/tires, adding battery and charging system, adding electronics (motor controllers, laptop interface, kill switches, navigation system, collision avoidance system), adding seats, adding air conditioning, adding side and rear doors, completing interior, adding windows, adding bumpers.

3.1.1. Vehicle Frame

The welding of the vehicle frame for the Version 1 test vehicle was completed in the early part of the project period, and suspension, brakes, and motors were integrated onto the vehicle. A picture of the build in progress is seen in Exhibit 4.

Exhibit 4: Aluminum Frame of Vehicle on Display at Research Triangle Park Event

Suspension, motors, motor driver, steering actuator, brakes, and brake actuators were subsequently integrated onto the vehicle. A subsequent design effort began to improve the suspension and drive train which we refer to as the Version 2 test vehicle.

3.1.2. Shell and Seats

The shell and seats of the vehicles were fabricated through thermoforming. Thermoforming was done at Accu-Form Polymers in Warsaw, NC which had one of the few large format thermoforming facilities in North Carolina. The mold for the shell is shown in Exhibit 5 and Exhibit 6.

Exhibit 5: Mold of Vehicle Exterior Shell

3.1.3.Air conditioning

A desktop air conditioning prototype unit was initially built in the lab for testing (Exhibit 8). An electric compressor was connected to air conditioner parts from a typical automobile to complete the system. Elements, some of which were adopted directly from AC car components, included an evaporator, condenser, dryer, and release valve. All the parts for the air conditioning were assembled and the air conditioner was qualitatively evaluated. As next steps, the AC unit was integrated into the Version 1 Test Vehicle and qualitatively measured. Next steps include a partial redesign of the interior ceiling to better fit the evaporator unit, and a method to better quantify the overall performance.

Version 1 Test Vehicle

Midway through the project, our first vehicle reached successful completion and underwent significant testing. Major areas of development included:

1) Shell and seat attachment to frame
2) Onboard Air Conditioner testing
3) LiDAR development and testing
4) Controller board testing

Exhibit 6: Mold of Shell with Thermoformed Shell

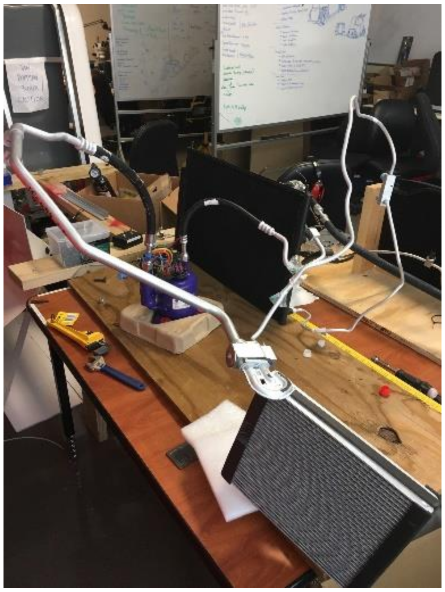
Mold (on left) was used to thermo-form shell part (on right).

Exhibit 7: Vehicle Close-up and Rendered Rear View

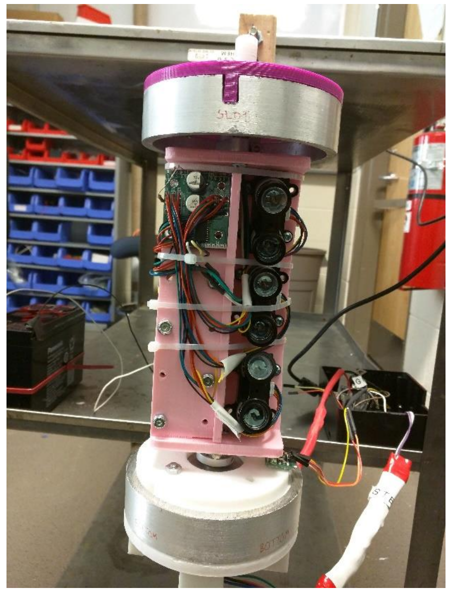
Vehicle close-up in lab

Egress Rear Door

Exhibit 8: Air Conditioner and LiDAR



AC Prototype Setup



6-Beam Rotating Lidar

Version 2 Test Vehicle Design

For the Version 2 Test Vehicle, lessons learned during construction and testing of the initial vehicle were incorporated into this vehicle's design. Notably, improvements were made to the suspension and drive train, as well as optimizing the vehicle frame for stiffness. Primary differences between the Version 1 and Version 2 test vehicles include:

1. A single central motor and drive shaft was replaced with two rear hub motors
2. The rear suspension was modified/simplified to accommodate the rear hub motors, necessitating the testing of several iterations (see

3. Exhibit **13**)
4. Better springs were incorporated into the suspension system (see Exhibit 12)

Exhibit 9: Final Vehicle Build

Exhibit 10: Suspension and Wheel Alignment Analysis

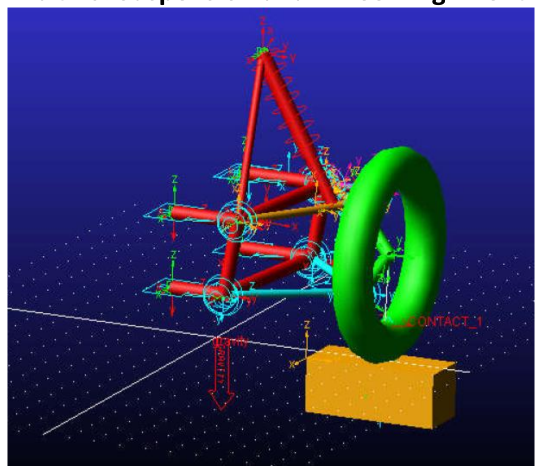
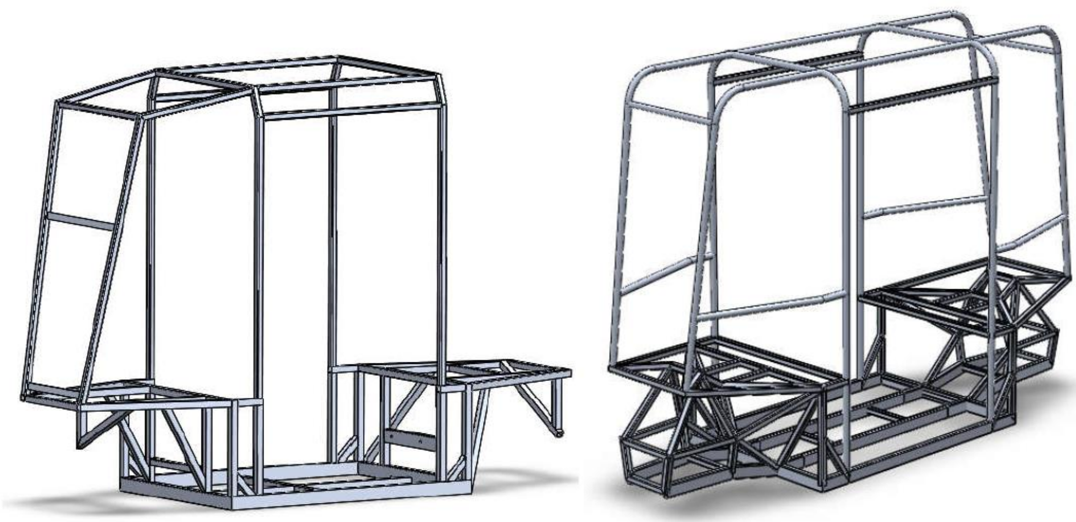
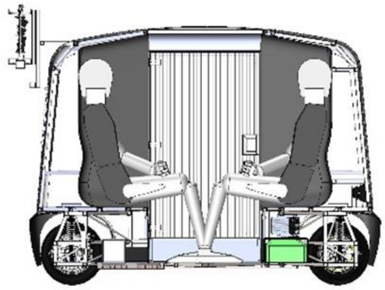


Exhibit 11: Comparing Vehicle 1 Frame to Vehicle 2 Frame



The Version 2 Test Vehicle offers an improvement in suspension from the first. We opted to use in-wheel hub motors for the drivetrain. This was chosen because of the difficulty in designing an independent drivetrain for such a narrow vehicle. With the motors in the wheels, this eliminates the need to use CV axles and differential gearing.

Exhibit 12: Version 2 Vehicle Interior View and Suspension Layout



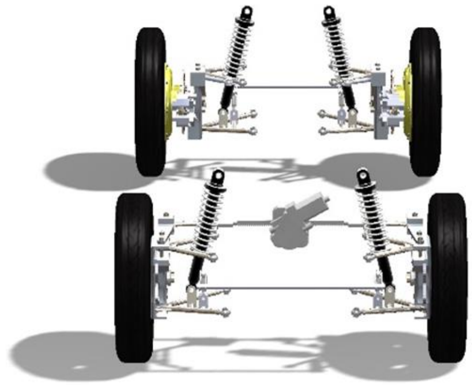


Exhibit 13: Version 2 Vehicle Welded Frame and Hub Wheel Testing

Welded Frame of Version 2 Vehicle. In-wheel motors are located in the rear wheels in the hub.

Navigation was successfully integrated and demonstrated. We initially started with a UWB localization solution. This solution required stationary antennas to be setup around the perimeter of the vehicle course, but eventually, we moved to a differential GPS solution with just a single base station providing cm level accuracy.

Exhibit 14: Version 2 Vehicle Welded Frame Top and Bottom

Exhibit 15: Customized Shocks with Wheel Steering Assembly

One of the changes from Version 1 to Version 2 is the addition of in-wheel motors. These pictures show the testing of the motor (located in the hub of the wheel).

The Version 2 vehicle is currently being finalized in its construction. Most of the mechanical elements have been finished (see Exhibit 14). We have waited to put on the final shells and windows until we add in the wiring and electronics.

3.2. Control and Sensors

3.2.1. Vehicle Controller Board

As part of the vehicle manufacturing effort, we designed, tested, and integrated a vehicle controller into the vehicle. The vehicle controller directly controls the brake actuators, steering actuator, and main motor drive. The system was designed with redundancy in mind for the braking. There are four brakes, one on each wheel with two vehicle controllers, each controlling two brakes. Should a brake fail, there are still 3 brakes that are operational. Should a vehicle controller fail, the other controller can still apply brakes to two of the wheels. A high-level schematic of the vehicle control system is shown in Exhibit 17 and

Exhibit **18** and a complete schematic of the overall vehicle electronics is shown in Exhibit 16.

Exhibit 16: Electrical Connection Diagram

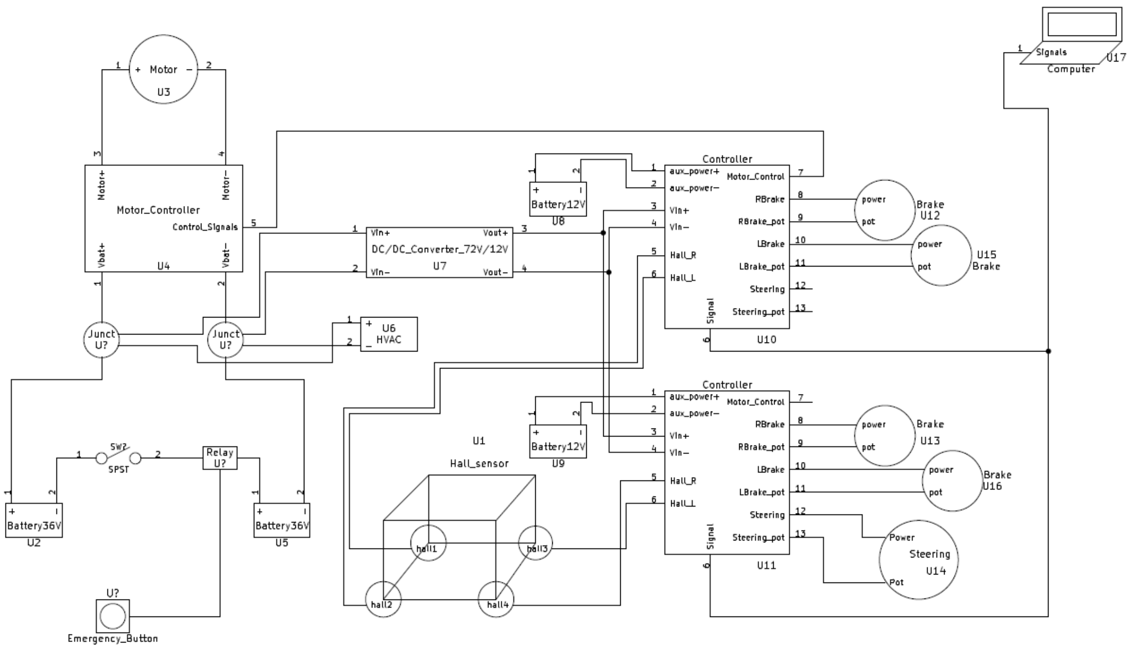


Exhibit 17: Controller Board and Seat Panel Electronics

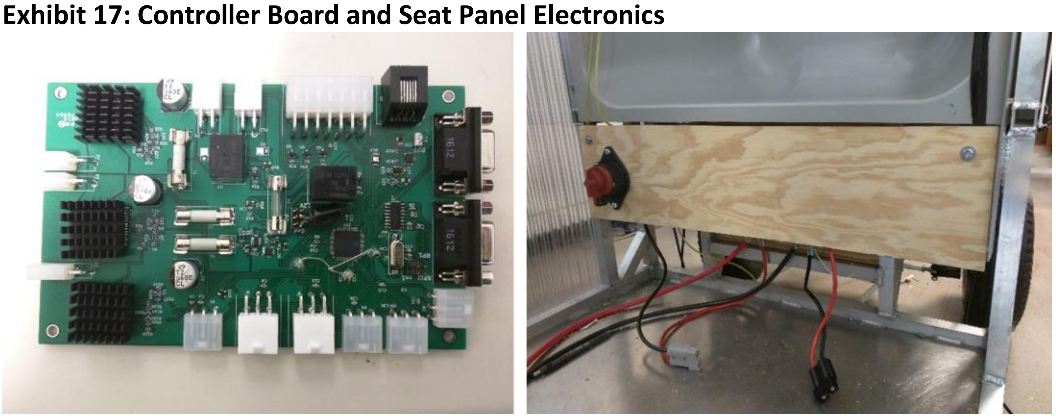


Exhibit 18: Controller Board with Enclosure

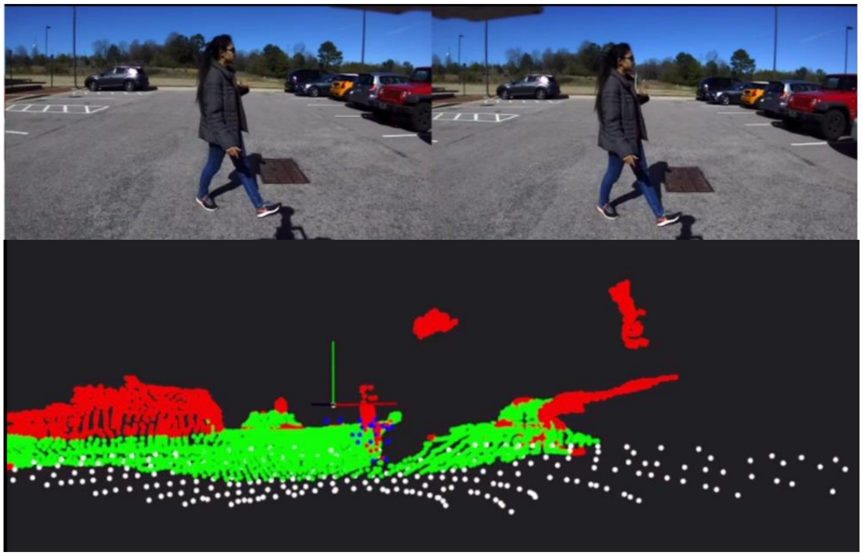
6-Beam Rotating Lidar

Lidar is a laser based 3D sensing system used in conventional autonomous cars. We have developed a less expensive variant that operates effectively at low speeds (Hollar, 2017). Exhibit 19 shows the recent prototype we are developing. The LIDAR is one of the two major sensors (the other being cameras) that will be used for navigation and collision detection.

Exhibit **20** below shows the 3D point cloud from the LiDAR on the vehicle. Green denotes the ground while red denotes obstacles.

Exhibit 19: In-House 8-beam LiDAR

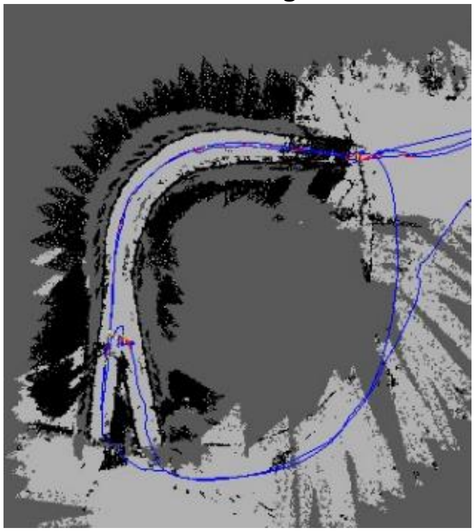
Exhibit 20: Ground Truth and Obstacle Recognition with LiDAR



3.2.2. Stereo Camera

In addition to LiDAR, we used a stereo vision camera to augment obstacle detection and vehicle navigation. For example, we are using the vision system to develop a 3D area of its surrounds which in turns tells the vehicle the drivable areas. Below is a figure showing the 3D mapping of the RTAB-map algorithm using our stereo camera.

Exhibit 21: SLAM through stereo vision with RTAB-map

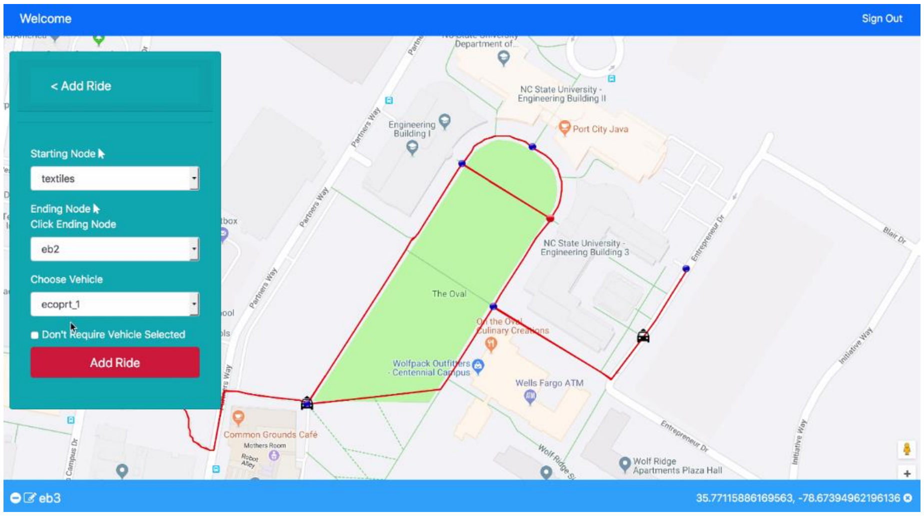


RTAB-map based off of stereo vision

3.2.3. Cloud Based Vehicle Fleet Manager

As part of the multi-vehicle tracking and control, we developed a first draft cloud-based, vehicle network controller. For a single vehicle, we intend to control it locally, but as we increase the number of vehicles, a team of graduate and undergraduate Computer Science students have developed a server based solution that allows vehicles to be controlled automatically. The web-based management panel allows one to create paths and stations which the vehicles then can follow based on rider requests. Though it is just a minimum viable prototype at the moment, this serves as the basis for a more sophisticated version as we add more vehicles to the network over time.

Exhibit 22: Cloud Based Vehicle Network Controller



3.3. Pilot Testing

The testing of the vehicle was broken down into three phases. The first phase tests the vehicle on a test track located right outside the building of the vehicle lab. Phase 2 tests the vehicle on an isolated parking lot area. The goal is to run identical tests located in different environments. Phase 3 is the final test where we take passengers on the vehicle to capture ridership information. Initially for the university's IRB approval (Institutional Review Board), we simplified the approval process by seeking approval of just Phase 1, and with success, we would then seek approval for phases 2 and 3.

For each phase, we established a set of success metrics need to proceed to the next phase. These success metrics are used to establish the functionality and safety of the vehicle. For phase 1, for example, the success metrics are described below:

Accuracy of Route

- Route #1 path accuracy within 1 foot over 100 ft of travel
- Route #2 path accuracy within 1 foot over 100 ft of travel

Obstacle Detection and Avoidance – vehicle traveling at 3mph

- Stationary Ball in path 1 ft diameter
- Stationary rectangular cutout (1ft x 3ft) in path
- Ball (1ft diameter) moving perpendicular to path at 3 mph 10 ft in front
- Rectangular cutout (1ft x 3ft) moving perpendicular to path at 3mph 10 ft in front
- Test subject walks perpendicular to path at 3mph 10 ft in front
- Bicyclist test subject rides perpendicular to path at 3mph 10 ft in front
- Stationary car in path of vehicle

Pedestrian Interaction with Vehicle

- Pedestrian Walk #1. Pedestrians (researchers) walk per "Demonstration and Survey protocol". Done 7 times
- Pedestrian Walk #2. Pedestrians (researchers) walk per "Demonstration and Survey protocol". Done 7 times
- Pedestrian Walk #3. Pedestrians (researchers) walk per "Demonstration and Survey protocol". Done 7 times
- Success measured when vehicle stops within safe distance from pedestrian (distance depends on type of walk)

Endurance testing

- Run vehicle on test path continuously for 1 hour at a time for a total of 5 hours
- Loading, transporting, and unloading passengers (researchers) in autonomous mode done 15 times with no human interference

Different from Phases 1 and 2, Phase 3 will include testing with unaffiliated passengers and pedestrians:

- Phase 1 – Testing Ground
- Phase 2 – Second Testing Ground
- Phase 3 – Passenger Testing at go-Live Location
    - Single-Vehicle, 100 ft Separated Route Live Testing – No Passengers
    - Single-Vehicle, 400 ft Separated Route Live Testing – No Passengers
    - Single-Vehicle, 400 ft Separated Route Live Testing with (non-researcher) Passengers
    - Single-Vehicle, 400 ft Non-Separated Route Live Testing with Passengers with controlled pedestrians
    - Single-Vehicle, 400 ft Non-Separated Route Live Testing with Passengers with free-form pedestrians

An image of the Phase 1 testing area is show in Exhibit 23.

Exhibit 23: Phase 1 Testing

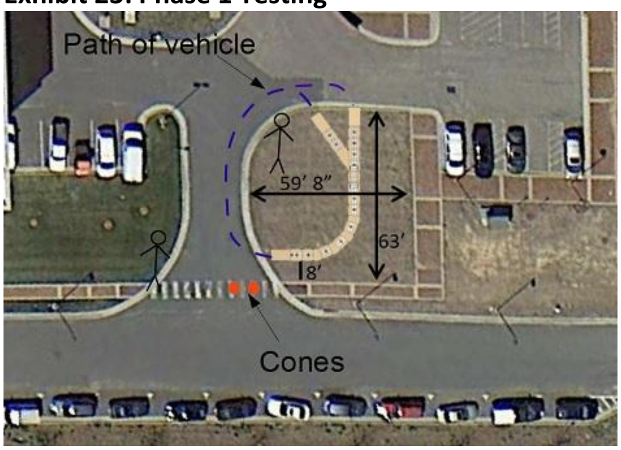


Exhibit 24: Proposed Route on Centennial Oval

A location for Phase 3 was originally proposed near the Hunt Library running from the Oval Dining facility to the Hunt Library. However, with the recent construction of the Oval Engineering Building, the area was not possible. We are currently still exploring a site for Phase 3 testing.

3.4. First Vehicle Testing

Initial navigation used an Ultra-wideband positioning system from Wiser Systems, Inc. We migrated to a differential GPS solution offered by Swift Navigation (Piksi Multi). With d-GPS, we are able to get cm accuracy positioning using just a single base station. The solution can be scaled to allow reliable navigation over half a mile from the base station. Integration of the camera obstacle detection/Lidar detection and navigation system is still being worked on. We have migrated from a Windows based controller solution to a Linux Robot Operating System (ROS). The goal of moving to ROS was to provide a modular framework on which to build. One of the challenges was integrating the navigation subsystem with the obstacle detection of the LiDAR and Stereo Camera. Our current ROS solution has enabled that integration and we are currently testing its performance in Phase 1.

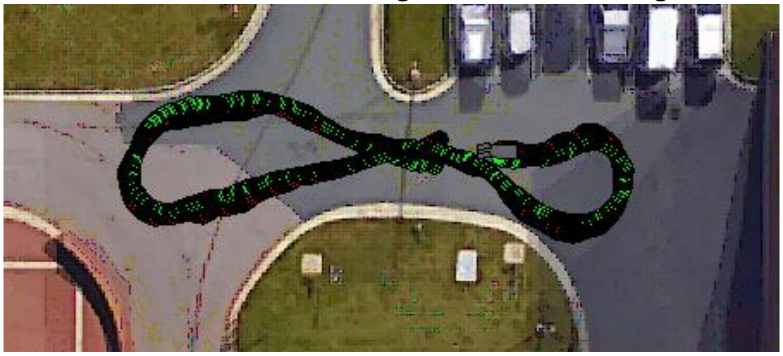
As part of Phase 1 testing, we performed some initial obstacle detection tests. In the image below, the vehicle uses the Lidar to stop before it hits traffic cones.

Exhibit 25: Snapshot of video of vehicle stopping in the presence of an obstacle (traffic cones)

3.5. Autonomous Testing

The vehicle has been tested for autonomous navigation. A captured image of the autonomous run for Phase 1 is shown in Exhibit 26. The vehicle successfully followed a predescribed path. We have recently migrated from a Windows operating system to that of Robot Operating System, so we are re-validating the path following we were able to demonstrate in the Windows OS. Further, we are still in the process of testing autonomous path following with obstacle recogniation.

Exhibit 26: Path of Vehicle During Autonomous Driving



A second vehicle was constructed and is being tested for dynamic performance and general operation (Exhibit 27). Overall, preliminary testing of the in-wheel motors was successful. Additional work of this vehicle includes finalizing wiring and installing power electronics, integrating the LiDAR and camera sensors, and adding the shell and some miscellaneous components. Testing shows that torque and acceleration are more than adequate. Furthermore, three more vehicles utilizing this design are currently being manufactured.

Exhibit 27: Second Vehicle Build

3.6. Future Testing

It is important to note that the results of this NCDOT project capture a snapshot of the development of EcoPRT. Ongoing work includes the finalization of the Version 2 Vehicle which has the second generation design. Further, we are actively manufacturing three more vehicles (vehicle #3 thru #5). Having moved from a Windows based operating system to a ROS (robot operating system) we are nearing a release of the software which will allow us to complete Phase 1 of the IRB and start Phase 2. Furthermore, as referenced, we are under development of a cloud based fleet management solution which in the future will enable us to coordinate the travel of multiple vehicles simultaneously.

4. Potential User Feedback: Focus Groups and Intercept Surveys

The challenges of developing EcoPRT into a viable automated microtransit system extend far beyond just questions of vehicular engineering, object detection, and routing algorithms. There are fundamental questions of how many future passengers would use an EcoPRT-type system. For this reason, the research team conducted three focus groups and administered intercept surveys with students, faculty, and staff on the NCSU campus. For each mode of data collection, participants were asked about their current modes of travel (both to and on campus). Then the EcoPRT concept was explained and participants were asked for their opinions, thoughts, and concerns about the system.

4.1. Student Focus Group

The first focus group took place on March 27, 2018 during an upper-level engineering class of approximately 30 students. This atypically large focus group was chosen for two main reasons. First, although engineering students may not be a representative sample of the entire NCSU student population, they travel frequently between Centennial Campus (where engineering classes are often held) and the Main Campus; thus, they may have more experience with using buses, bikes, and other modes to travel between the campuses and may have the most to gain if EcoPRT proves viable. Secondly, as the students were taking a course on highway design, they were well primed to situate their personal travel experiences within a feasible transportation framework.

The majority of the students currently travel across campus via the Wolfline buses. They generally found them to be quick and convenient, although several students complained of “rush hours” occurring after large classes let out and the a few “transit deserts” where buses do not travel to. They felt that both the hills and the difficulty of crossing Western Boulevard made walking and biking poor options. The students were clearly cost-conscious as well, stating that bikesharing (this was prior to the Summer 2018 introduction of shared electric scooters to NCSU) was too costly and inconvenient to use regularly and that driving was only a viable option after five PM, when parking was free.

The EcoPRT concept was then explained to the students with a slideshow showing pictures and potential deployment scenarios. These students were generally positive about the potential of EcoPRT, but wondered how competitive it would be in practice. They felt that in order for it to be better than the current bus situation it would be have to be at least as fast and that there should be no more than a few minutes of wait time. They thought it should cost under $2 per trip, but felt that it would be better if it was included as part of student fees in order for it to truly compete with buses. They thought it might have more of an advantage in bad weather.

They were worried about how many vehicles would be necessary to replace buses, or even to augment them. Showing their engineering backgrounds, they were also concerned that when the vehicles traveled through busy sidewalks or plazas that they would have to stop continuously in order to allow pedestrians to pass. A few participants were hesitant about sharing the vehicle with an unknown passenger, although others felt fine as long as the fellow passenger was a NCSU community member.

4.2. Staff and Faculty Focus Groups

On May 17, 2018, the research team conducted two focus groups with staff and faculty members at the Hunt Library on Centennial Campus. The participants were primarily recruited through the WolfTrails listserv, which is composed of NCSU community members who commute or wish to commute to campus using alternatives to single-occupancy vehicles; this is a program run by the NCSU transportation department that facilitates alternative commute options including carpooling, vanpooling, transit, walking, and teleworking. Because one of the potential benefits of EcoPRT is helping to solve the first mile/last mile problem of transit, the research team felt that this group could give valuable insight into how carless travelers might use EcoPRT.

There were six participants in the morning focus group and ten in the afternoon session. While some of the participants occasionally drove alone to commute to campus, the majority of them used alternative modes. The morning session was primarily composed of vanpoolers and bus passengers, while about half of the afternoon group commuted by bicycle. They all enjoyed these alternative commute modes, which were primarily motivated by environmental concerns, as well as convenience. Participants who commuted on one of the express buses (e.g., from Chapel Hill or Durham) said that one issue they had was if they had to return home midday, when the express was not running.

Most of the participants had days (a couple of times a week to a couple of times a month) when they needed to travel across campus further than they could comfortably walk. When they needed to do these trips, several participants said they used the Wolfline buses, while other participants said they had never figured out how the buses worked. The cyclists generally used their bicycles, while one person had a colleague drive her across campus for a weekly trip she needed to make.

Most participants thought they would be able to make these cross campus trips with a fully functional EcoPRT system. One person with physical mobility issues thought that EcoPRT would be quite useful and all the participants agreed it could be very helpful for many disabled travelers. One participant goes across campus frequently, but usually with more materials than she could carry easily on the bus, which would be her preferred choice. Because of this, she often drives in to campus on those days or uses a colleague's car, but she felt that she would be able to use EcoPRT in these situations.

The morning group was generally more positive and excited about the EcoPRT concept than the afternoon group. The morning participants thought it would provide them with more options and flexibility in their routine. They were not worried about the driverless aspect of the vehicle, nor about sharing the vehicle with another passenger, unless it slowed down the trips. They were concerned with the vehicle being slowed down by navigating through paths crowded with pedestrians and thought that it should be equipped with some sort of "Walk/Don't Walk" signal.

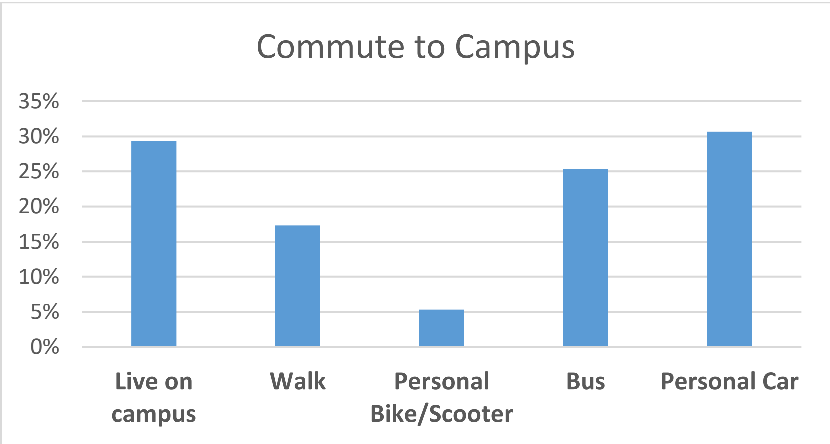
The afternoon group, while interested, were more skeptical about the EcoPRT concept for two main reasons. The first was about safety and reliability issues. They wanted EcoPRT to have a proven track record before they rode it themselves. The second reason was they felt that EcoPRT could be diverting resources from transit, while increasing traffic in such a way as to negatively affect bicyclists and other roadway users.

4.3. Intercept Survey

During the week of November 26th to November 30th, the ITRE research team conducted an intercept survey with 75 individuals. An EcoPRT vehicle was set up at two different locations near the "Oval" on Centennial Campus on different days: near the Wolfline bus stop between Engineering Buildings I and II and by the southern entrance to the food court in Tower Hall. Passersby were asked to stop and learn about the EcoPRT concept while they examined the vehicle, after which they were given a short survey, included in Appendix 1. Full Results are included in Appendix 2.

Overall, 63 (84.0%) of the respondents were NCSU students and 10 (13.3%) were staff or faculty who work on Centennial Campus. Exhibit 28 shows the breakdown of how the respondents commute to campus (multiple answers were allowed). The two largest categories, both at 32.0% were Live on Campus and Personal Car, followed by Bus (25.3%) and Walk (17.3%). Therefore, most of the respondents are familiar with using alternative forms of transportation when travelling across NCSU.

Exhibit 28: Respondents' Commute to Campus

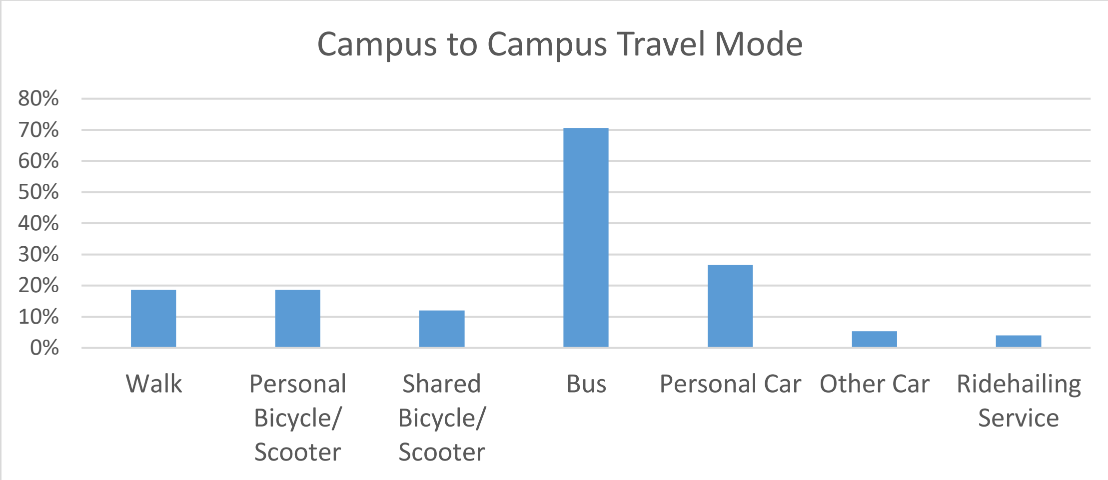


Once on campus, 74.6% of the respondents currently travel between Main and Centennial Campuses more than once a week, as shown in Exhibit 29. Using the NCSU Wolfline bus is the most popular choice for these trips (70.7% of respondents use bus as one of their options), with personal car as the second top choice at 26.7% (see Exhibit 30 for complete results).

Exhibit 29: Travel Frequency Between Main and Centennial Campuses

Daily	34.7%
2-3 Times per Week	40.0%
1 Time per Week	8.0%
Monthly	9.3%
1 Time per Semester	1.3%
Fewer than 1 Time per Semester	6.7%

Exhibit 30: Campus to Campus Travel Mode



The mode the respondents used to commute to NCSU (Exhibit 28 above) was also somewhat indicative of the mode they used from cross campus travel, although bus was always a popular mode. For instance, 71.4% of respondents who walked to campus also walked across campus at least part of the time (busing was their second choice at 42.9%). Those who bused to NCSU, also bused across NCSU (85.7%), with personal cars and shared bicycles/scooters as their second choice (21.4%). For people who drove to NCSU, 56.5% said they would drive at least sometimes when crossing campus and an identical 56.5% said they would bus at least sometimes. For those living on campus, buses were the clear favorite at 94.7%, with bicycles coming in number two at 31.6%.

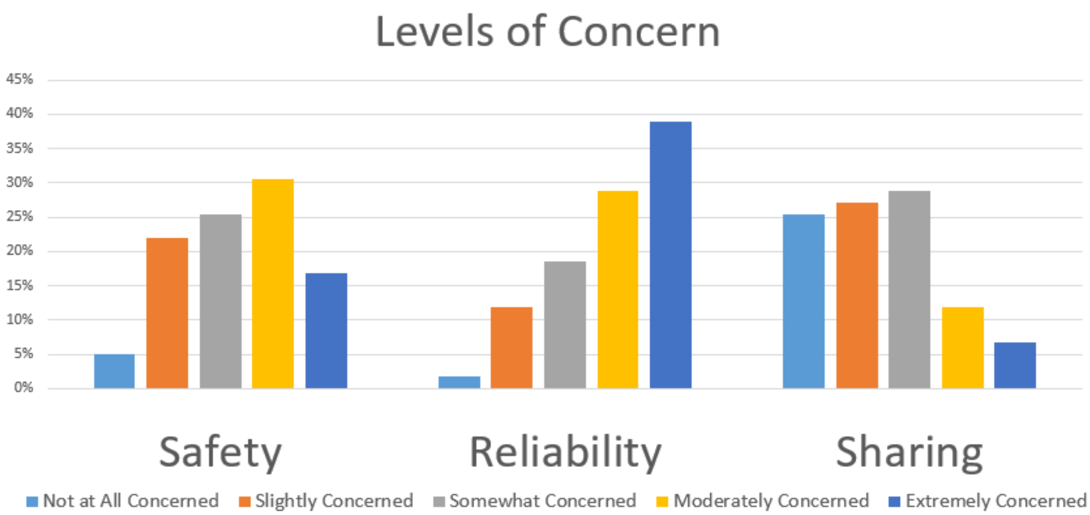
Once the participants were shown the vehicle and had the EcoPRT concept explained to them, they were asked open-ended questions about what they liked about the concept, what their concerns were, and how often they thought they would use it for future trips across campus. In terms of what they liked about it, 33.8% found it "cool" or "interesting", 23.9% liked the small size, 21.1% liked the convenience, while 14.1% liked the fact it was autonomous and 7.1% mentioned its use of green or electric technology. They offered comments like:

- "I like the idea of on-demand semi-private transportation which could be available when other services are not available. The idea of a nonstop service from place to place."
- "I am huge fan of automated transport and I like how it can operate off the roads."

For their concerns, over half (56.9%) brought up safety issues, including both within the vehicle as well as for nearby pedestrians. The rest of the concerns dealt mainly with logistical details, such as would vehicles be reliably available (12.5%), how much would it cost (15.3%), and more specific questions such as parking or its effect on buses (15.3%).

These answers match up loosely with later questions, where the participants were asked on a five-point scale how concerned they were about safety, reliability (time and availability), and sharing the vehicle with another passenger (see Exhibit 31). While safety was an obvious concern to state in the open-ended questions, reliability factors were more of a factor to the respondents. While 47.4% of respondents were moderately or extremely concerned about safety, a substantially larger 67.8% were moderately or extremely concerned about EcoPRT's reliability. This may indicate that many participants predict that there will be sufficient safety safeguards in the future, but are still worried that the overall system will not be convenient or fast enough to compete with other modes. Additionally, only 18.7% said they were moderately or extremely concerned about sharing an EcoPRT vehicle with another passenger. This may possibly be due to younger adults being more familiar with modern sharing culture or it may be that they are fine with sharing the vehicle with other members of the NCSU community, but perhaps not the general public.

Exhibit 31: Levels of Concern

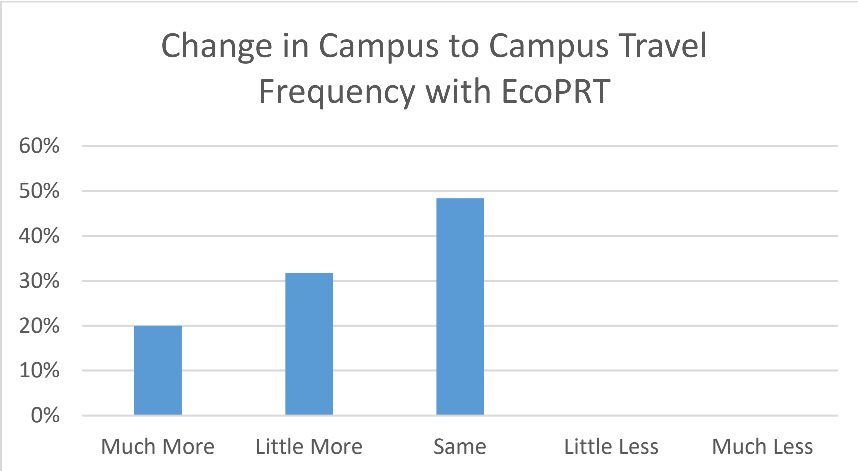


When asked how often they would use EcoPRT for future trips across campus, respondents gave the following answers:

- Daily: 14.1%
- More than once a week/very often: 19.7%
- Weekly: 7.0%
- Once or twice a month: 4.2%
- Rarely/not often/never: 7.0%
- It depends: 31.0% (9 of these 22 respondents said they would use it as much as needed).

A connected question to this was when participants were asked if EcoPRT would change their frequency of cross campus travel, the results of which are shown in Exhibit 32. This is an important issue as it helps determine whether there are trips that the traveler would *like* to make, but does not currently make because the mode choice is not sufficient. No respondent predicted that EcoPRT would reduce their travel, since, unsurprisingly, the addition of a new mode should not reduce the demand. About half (48.3%) predicted no change, while 31.7% predicted they would cross campus a little more frequently and 20.0% predicted they would cross campus much more frequently. This implies that a viable EcoPRT system could increases the overall number of trips, by improving access or convenience of the potential travelers. Those respondents who commute to NCSU in personal cars are the most likely stay the same (63.2%) while those who bus to campus are the least likely to stay the same (63.2%).

Exhibit 32: Change in Campus to Campus Travel Frequency with EcoPRT



The survey also asked various questions about the possible pricing of EcoPRT. Respondents were asked to which pricing models they thought EcoPRT could employ, as shown in Exhibit 33 (they could choose more than one answer). Not surprisingly, "free" was the top choice, with student fees and paying per trip tied for second. This matches up to discussions from the focus groups, where students thought it should be incorporated into the fees. Those individuals living on campus were the mostly likely to think student fees were a good option (66.7%), while only 10.5% of those driving to campus thought fees should be used. This is possibly because students living on campus feel they are better able to utilize the benefits student fees bring, while drivers, who may live farther away, could feel they are not able to take advantage of them.

Exhibit 33: EcoPRT Pricing Models

Student fees	37.3%
Pay per trip	37.3%
Monthly subscription	8.5%
Free	78.0%

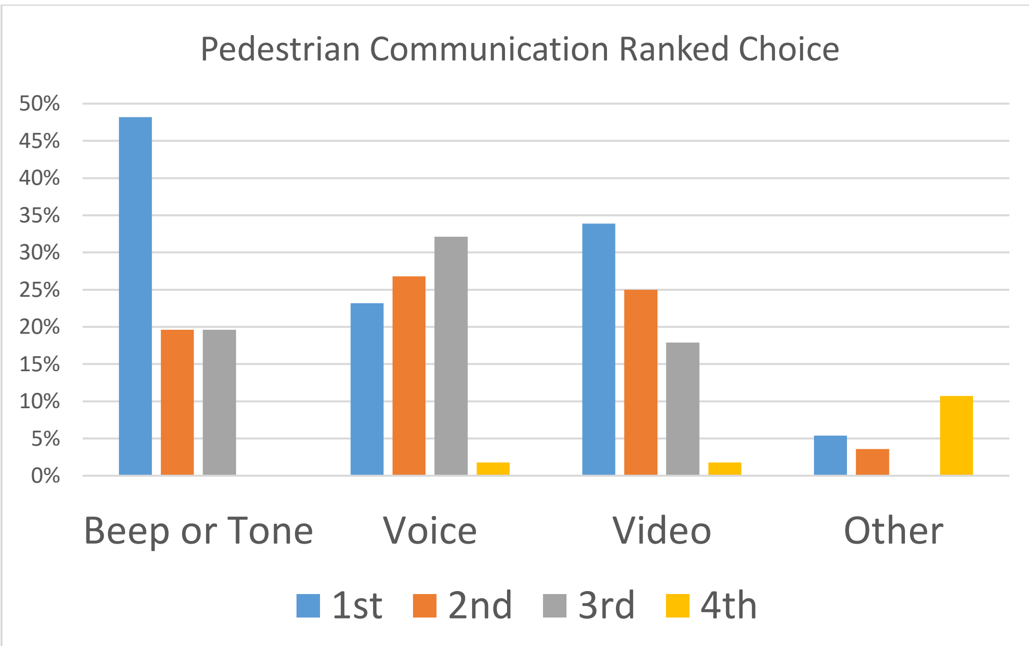
Respondents were also asked about their willingness-to-pay for an EcoPRT trip, with four options: $1, $2, $3, or other. The results are broken down below:

- $1: 37.3%
- $2: 33.9%
- $3: 8.5%
- Other: 8.5% (all listed a price of less than $1)

As discussed in the focus group section, many students are extremely cost-conscious. While the novelty of an automated vehicle would doubtless increase demand, in the long-term the price may have to be low in order to compete with the free Wolfline transit system. Further research on this topic might benefit by examining how the shared bicycles and scooters are being used on campus, where the cost of a cross campus trip can range from $2 to $5 or more.

Finally, in order to aid the EcoPRT engineers working on advanced models of the vehicle, the respondents were asked about communication between the vehicle and pedestrians. When an automated vehicle is sharing paths with pedestrians, particularly on a crowded campus like NCSU, it is not only vital that the vehicle be able to detect and avoid pedestrians, bicyclists and other obstacles, but that it inform pedestrians of its intent. For instance, the ideal vehicle would be able to tell a pedestrian when it is waiting for the pedestrian or when the pedestrian should wait for it. With human drivers, these communications are often done with hand-waving or eye contact, but driverless vehicles pose more challenges. The research team therefore asked the survey participants to rank the following choices: Beep or tone, Voice, Video display (e.g., a “walk signal”), and other. The results are shown in Exhibit 34. An audible beep or tone was the top ranked choice, followed by a video display. In the next phase of EcoPRT (Research Project No. 2019-028), these issues will be investigated further in conjunction with the EcoPRT vehicle.

Exhibit 34: Pedestrian Communication Ranked Choice



5. EcoPRT Benefit-Cost Analysis

5.1. Project Description

As discussed previously, a formal benefit-cost analysis (BCA) and economic impact analysis (EIA) was conducted for this project using best practices associated with transportation planning. There are numerous long-term impact areas that a fully-operational EcoPRT system could provide:

- **Economic Competitiveness:** The construction of the EcoPRT system will be the first of its kind in the U.S., bringing jobs and economic productivity to NC State, Raleigh, Wake County, and the entire state of North Carolina.
- **Environmental Sustainability:** Bus trips and delay will be reduced and mode shifts from bus and single-occupancy (SOV), mostly gasoline-powered engine vehicles to vastly more efficient electric-powered vehicles will occur, leading to environmental cost savings, lower reliance on foreign fossil fuels, and emissions reductions.
- **Safety:** Modal shift from single occupancy vehicle and Wolfline bus travel to the EcoPRT system will improve overall safety of students, faculty, and staff.
- **Livability:** With the introduction of the EcoPRT system, NC State students, faculty, and staff will have greater modal options to consider. Travel cost and time savings will help to improve connectivity between Central Campus and the growing Centennial Campus.
- **State of Good Repair:** The EcoPRT system will result in extending the state of good repair lifecycle of NC State, Raleigh, and NCDOT funded roads throughout the NC State campus; in addition, this project will improve the state of good repair for some NCSU Wolfline buses.
- **Other Built Environment Benefits:** The EcoPRT system will allow for the construction of surface-level parking at the university's Centennial campus, rather than the more expensive option of constructing a parking structure on the center of campus. This is because the EcoPRT system will allow for the efficient and timely transportation of faculty, staff, and students from these surface lots to Central Campus.

It is worth noting that there are far more additional monetizable and non-monetizable benefits beyond the scope of this analysis. For example, past research has shown the availability of multiple travel options on a university campus can, in many cases, lead to long-term shifts in how students, faculty, staff, and visitors travel to and from a university campus from locations elsewhere (Balsas, 2003). These long-term shifts in travel behavior are more complex, and therefore much more difficult, to model given the level of uncertainty associated with this project. Furthermore, as discussed in Section 4.3, 90% of surveyed students stated that they would be willing to paying $1 or more for each trip, fees that were not included in this benefit-cost analysis. While this analysis did not include these benefits into this analysis, if these benefits were incorporated into a more in-depth study it would likely increase the benefit-cost analysis score in a beneficial direction for the NCSU EcoPRT project.

5.1.1. Discount Rates

Federal guidance and other transportation experts recommend that any BCA analysis discount future benefits and costs to a base year and present discounted rates of both the stream of benefits and the stream of costs.[1] For this analysis, final streams of benefits and costs are presented at a 7% and 3% discounted rate.

5.2. Cost-Benefit Results

Exhibit 35 summarizes project costs and the quantifiable benefits of the project in terms of net present value. The net present value of all direct EcoPRT project costs, as well as evaluated benefits are shown in Exhibit 35: Benefit Cost Analysis SummaryExhibit 35 below. Factoring in savings from avoiding construction of a parking structure, the benefits have a net present value of $67.5 million over the 31-year analysis period (30 years + 1 year after the initial construction phase of one year), yielding a 4.30 to 1 benefit-cost ratio at a 7% discount rate. When not taking parking cost savings into account, the direct benefits of the EcoPRT project still outweigh the direct costs.

Exhibit 35: Benefit Cost Analysis Summary

Category	Present Value at 7%	Present Value at 3%	Undiscounted
Construction/M&O Costs	**$20,477,236**	**$21,816,711**	**$23,836,341**
Evaluated Benefits			
Value of Time Savings	$40,941,471	$66,290,459	$105,660,463
Vehicle Operating Cost Savings	$1,777,894	$2,882,739	$4,600,522
Safety Benefits	$330,659	$534,878	$851,824
Parking Cost Savings to NCSU	$44,971,872	$55,997,405	$73,415,300
Total Evaluated Benefits	**$88,021,895**	**$125,705,480**	**$184,528,109**
Net Present Value	**$67,544,659**	**$103,888,769**	**$160,691,768**
Benefit Cost Ratio	**4.30**	**5.76**	**7.74**

5.2.1. *Benefit Calculation Assumptions*

The benefits of the project are derived by comparing conditions under a "Build" and "No Build" scenario. These scenarios are defined as the following:

No Build
Under the no-build scenario, the EcoPRT system is not constructed and current status-quo transportation conditions continue. As a result, traffic congestion from single-occupancy vehicles continues to grow, and expanded bus service connecting the Centennial and Central campus will need to continue to expand to meet demand. Furthermore, this scenario assumes that due to increased demand, a new, multi-level parking structure on Central Campus will need to be constructed of approximately 3,200 vehicles.

Build
The build scenario assumes the construction and operation of an at-grade EcoPRT system for a period of 31 years (1 year of construction plus a 30-year analysis period.). Specifically, this scenario assumes a total of $18.2 million will be invested to fully construct the EcoPRT system in Year 1, which would allow

[1] Department of Transportation Office of the Secretary of Transportation, Docket No. DOT-OST-2012-012; Fed. Register Vol. 77, No. 20, pp.4868.

75% of Wolfline trips to transfer to EcoPRT. This analysis also assumes a small mode share trip capture from personal automobile to EcoPRT. From there, this analysis assumes operations and maintenance costs, discounted at 3% and 7%. Finally, this scenario also assumes cost savings from what will no longer need to be built. Current university plans call for a parking structure to be built on the central campus. Due to the connectivity that the EcoPRT system will provide, the university will no longer need to construct this parking structure. Instead, the university can construct surface parking on land the university already owns near the Centennial campus, or use existing, under-utilized parking areas. The EcoPRT system, in conjunction with Wolfline transit will provide an affordable, efficient, and timely connection for those who park on the Centennial Campus to access the main campus.

5.2.2.Quantified Benefits

Value of Time Savings

Exhibit 36 below illustrates the quantified value of time savings over time. When a person can travel to their destination more quickly or more efficiently, there's an aggregated savings (or benefit) to society. These calculations assume an average Wolfline trip that takes 20 minutes would take 10 minutes with EcoPRT (see Section 5.5.5 5.5.5for a discussion of speed comparisons of different modes) and a replacement of some car trips.

Exhibit 36: Quantified Value of Time Savings

	Value of Time Savings		
Year	**Undiscounted**	**3% Discount Rate**	**7% Discount Rate**
2020-2024	$13,027,890	$12,276,756	$11,401,406
2025-2029	$14,292,100	$11,618,676	$8,919,360
2030-2034	$15,572,065	$10,920,901	$6,930,248
2035-2039	$16,869,424	$9,868,720	$5,353,599
2040-2044	$18,185,988	$9,491,075	$4,114,997
2045-2049	$19,523,755	$8,789,826	$3,150,329
2050-2051	$8,189,242	$3,324,504	$1,071,532
Total	**$105,660,463**	**$66,290,459**	**$40,941,471**

(See Appendix 3 for full, year-by-year table)

5.2.3. Vehicle Operating Cost Savings

In addition to benefits attributed to value of time, there are also savings that result from a reduction in other costs. Currently, the university operates Wolfline bus service to better connect the Central and Centennial campuses together. The EcoPRT will result in savings to the university because it will help replace some bus and car trips by transferring to them to these microtransit vehicles.

Exhibit 37 below illustrates the quantified vehicle operating cost savings over time.

Exhibit 37: Quantified Vehicle Operating Cost Savings

Year	Vehicle Operating Cost Savings		
	Undiscounted	3% Discount Rate	7% Discount Rate
2020-2024	$563,891	$99,371	$493,487
2025-2029	$619,103	$503,289	$386,355
2030-2034	$675,671	$473,846	$300,686
2035-2039	$733,736	$429,226	$232,837
2040-2044	$793,453	$414,078	$179,520
2045-2049	$854,994	$384,910	$137,946
2050-2051	$359,674	$146,012	$47,062
Total	**$4,600,522**	**$2,450,732**	**$1,777,894**

(See Appendix 3 for full, year-by-year table)

5.2.4. Safety Benefits

There are also net safety benefits derived from the EcoPRT system. The No Build scenario of this analysis assumes that students, faculty, and staff will continue to use less safe modes of travel, such as a personal automobile, to travel between each campus. As shown in Exhibit 38 below, this analysis found a total of $330,659 in quantified savings using a 7% discount rate.

Exhibit 38: Quantified Safety Benefits

Year	Safety Benefits		
	Undiscounted	3% Discount Rate	7% Discount Rate
2020-2024	$105,450	$99,371	$92,286
2025-2029	$115,621	$93,994	$72,158
2030-2034	$125,835	$88,251	$56,004
2035-2039	$136,096	$79,619	$43,193
2040-2044	$146,410	$76,412	$33,131
2045-2049	$156,781	$70,587	$25,300
2050-2051	$65,631	$26,644	$8,588
Total	**$851,824**	**$534,878**	**$330,659**

(See Appendix 3 for full, year-by-year table)

5.2.5. Parking Cost Savings to NC State

Finally, because the EcoPRT system will allow for the construction of surface-level parking at the university's Centennial campus it will result in savings to the university because the expensive option of constructing a parking structure on the center of campus will be avoided. As shown in Exhibit 39 below, the EcoPRT system will allow for the efficient and timely transportation of faculty, staff, and students from these surface lots to Central Campus.

Exhibit 39: Quantified Parking Cost Savings to NCSU

Year	Parking Cost Savings		
	Undiscounted	3% Discount Rate	7% Discount Rate
2020-2024	$33,241,455	$32,956,137	$32,623,699
2025-2029	$5,569,923	$4,526,191	$3,472,821
2030-2034	$6,301,857	$4,417,452	$2,801,517
2035-2039	$7,129,972	$4,168,814	$2,259,924
2040-2044	$8,066,909	$4,207,522	$1,822,832
2045-2049	$9,126,967	$4,106,428	$1,470,557
2050-2051	$3,978,216	$1,614,861	$520,523
Total	**$73,415,300**	**$55,997,405**	**$44,971,872**

(See Appendix 3 for full, year-by-year table)

5.3. Transferability Beyond NCSU

An AMT system like EcoPRT has the potential to be implemented at a variety of different types of locations. Anywhere where there is a large number of people going between many different origin/destination points at relatively low speeds (under 15 mph) for relatively short distances (under 3 miles), then EcoPRT may be the solution, particularly when shared-use paths can improve the system efficiency. Possible sites could include other universities, military bases, state fairs, large malls, retirement developments, downtown centers, large medical centers, business parks, and neighborhoods where EcoPRT can provide access to transit stations (relieving the first mile/last mile problem). Each type and, indeed, each specific site will have its own unique economic situation, but many of the findings from this benefit-cost analysis can be transferred to other locales. The following characteristics need to be considered:

- *Local Geography*: the layout and topography of the site will have an important effect on the economic sense of EcoPRT. If the main trips needed are to move spectators from a train station to a stadium all at once, then a larger shuttle or bus may be the best solution. But if the destinations are dispersed, then the flexibility of AMT makes it a better choice. Furthermore, the idiosyncratic barriers must be considered; if guideways are not needed, then the costs go down, but if the vehicles must frequently pass over busy streets, rivers, or train tracks, then costs will rise.
- *Trip Mode Transfer*: would EcoPRT generate new trips or would it capture trips from different modes? If EcoPRT can decrease SOV trips, then the gains could be high, but if it takes travelers off their bicycles, then the BCA must be adjusted accordingly, particularly travel time and safety savings.
- *Size of the Program*: The economies of scale mean that a small program might need to spend too much on initial infrastructure and ongoing maintenance to make it worthwhile.
- *Unique Factors*: At NC State, the ability to avoid building a new parking structure would enable enormous cost savings and similar situations in other sites could also hold benefits. For instance, certain locations might make it difficult for transit services to transport disabled passengers easily and conveniently, but EcoPRT might be able to provide door-to-door service.

5 NCSU Corridor Feasibility: Mobility and Accessibility Gaps

5.1 Introduction

As part of the project scope, the research team conducted a corridor analysis of NCSU. Although a perfectly operational EcoPRT system would, in the long-term, be able to access most of the NCSU campus, pilot testing and eventual implementation would likely be in steps. The team therefore investigated to see which areas of NCSU have the greatest need for a new mobility option, with emphasis placed on travel between Main and Centennial Campuses.

Travel across the campus of a large university like NCSU is fundamentally different than most types of travel. Students' class schedule dictate that large numbers of students arrive at specific destinations (i.e., classrooms) at specific times and then leave those destinations together a certain time later. While classes are probably their most time-dependent activity, students also have multiple other on-campus destinations, such as dining halls, libraries, medical facilities, and recreational facilities. Therefore, using zonal data to identify mobility and accessibility (M&A) gaps would be inaccurate and the research staff attempted a novel solution to determine these gaps on the NCSU campus.

5.2 Campus Travel

Transportation mode choice made by students and faculties could also be an important indicator to identify M&A gaps. According to the NCSU Student Travel Survey (2011), the majority of vehicle trips are the result of students driving to campus (over half) and daily cross campus travel (one-quarter). Compared with on-campus students who primarily chose to walk (or ride the bus, according to our survey discussed in Section 4.3), the mode choice for off-campus students is determined by distance to home and accessibility to campus. Despite the fact that driving speed is much faster than walking or biking, the trip time associated with driving can be higher than other modes, due to parking and other issues. Lastly, students may influence each other's choices. Wang found a spatial correlation in bicycle mode choice (*6*); neighborhoods with more cyclists enhance the attractiveness of the mode.

The M&A gaps between NCSU campuses generate negative impacts for students, as previous NCSU research shows that the inconvenience of travel between the Main Campus and the Centennial Campus can influence academic course selection. Most on-campus students live west of Main Campus and there are several travel options to Main Campus (e.g. walk, bike, transit). However, access to Centennial Campus poses a significant challenge for these students – they have to traverse Western Boulevard, which is a busy, 6-lane road and then travel along a 5-lane road, either Avent Ferry Road or Varsity Road. Neither of the selections is easy for travel due to high traffic volume, long signal phases, unshaded sidewalks and narrow bike lanes. There are four transit routes which operate between Main Campus and Centennial Campus, however none of the transit options can fully meet students' travel demand.

5.3 Mobility and Accessibility

Mobility is defined as access to transportation options; adding a viable EcoPRT autonomous microtransit system would by definition increase mobility options for those able to use it. Transportation options for students plays an important role in student travel demand modeling. However, traditional travel demand modeling focuses on highways and state-owned roads, with little research on campus travel.

Accessibility can have many meanings, such as the ability of accessing different activities, distance to transit stops, walking and waiting time for transfer. Meanwhile, Benenson (2010) argued that there is an obvious disparity between private and public transport accessibility. For the purposes of this study, accessibility is defined as the ability of accessing campus buildings by different transportation modes.

The 2011 Student Travel Demand Survey for the UNC system focused on the impact of student travel demand and choice on roads around the campus. As a result, the model based on the 2011 survey only considers four trip types that were specific to travel on- and off-campus. This section focuses on cross campus travel and three distinct on-campus trip types: 1) travel between on-campus home and on-campus activity by on-campus students; 2) travel between on-campus activity and another on-campus activity by on-campus students; and 3) travel between on-campus activity to another on-campus activity by off-campus students. Travel demand for these trips are believed to be good indicators for understanding cross campus travel.

5.4 Measuring Accessibility and Mobility Gaps

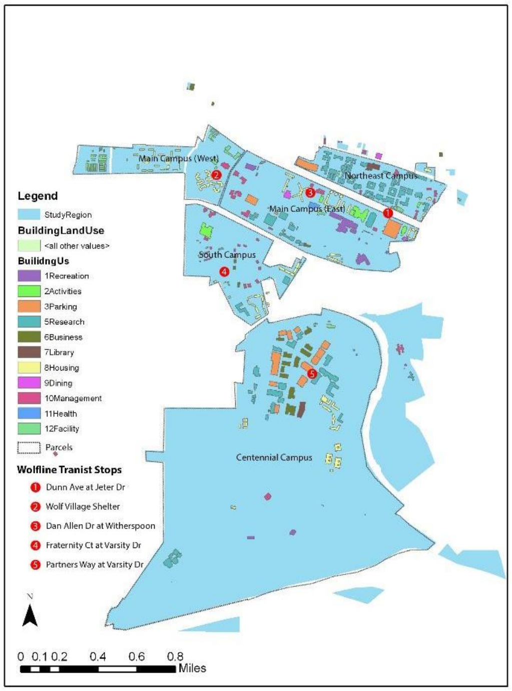
In this study, we calculate mobility and accessibility for each of the buildings in the NCSU study area. This micro-level analysis focuses on identifying the existing accessibility and mobility gaps for typical cross campus trips. Three components are included in the measurement of accessibility: 1) land use, 2) transportation mode, and 3) time. Mobility is measured by the time travel between designated locations using different modes. The predicted performance of EcoPRT is evaluated by the total travel time in comparison with other modes (walking, biking and transit).

5.4.1 Study Region

NCSU is located west of downtown Raleigh on 2,099 acres (NCSU, 2008). With the development of Centennial Campus over the past two decades, an increasing number of students and faculty move between Centennial Campus and other campuses. This study uses Centennial Campus, three adjacent campuses and the related intra-travel corridor as the study region. The main campus spreads over a long distance from west to east and is larger than other campuses. Main campus is split along Varsity in order to study accessibility between these two sub-areas (see

Exhibit **40**).

Exhibit 40: NCSU Building Type Map



5.4.2 Calculation of Accessibility

Campus building accessibility was measured by summing the accessibility for walking, biking and transit, as explained below. The study calculates accessibility by calculating travel time and reachable square footage from each building to all other buildings. Mode-specific measurement varies by building location, usage, and user mode choice, as discussed below.

a. Building Use Grouping

Buildings in the study area are grouped to 11 land uses (see Exhibit 41). For each building, the total square footage is calculated by multiplying footprint by number of floors. The NCSU University Architect provided the building footprint shape files joined with a facility database. To simplify the calculation, the study categorizes the uses of recreation, activities, library, dining, and health all as Service. Research/Classroom consumes 5,178,221 square footage (SF), which is the largest square footage in all categories. Health only consumes 69,345 SF, which specifically refers to the NCSU Student Health Center in Main Campus East. The study focuses on buildings in these four categories for the trip purpose analysis. In the study region, there are two major libraries, D.H. Hill Library and James Hunt Library, located on Northeast Campus and Centennial Campus respectively. By categorizing different building uses, the different kinds of trips can be identified. In this study, we focus on three main kinds of trips, specifically residence to research/classroom, residence to service, and research/classroom to service.

Exhibit 41: Building Area for Different Parcels

TYPES	PARCELS (SF)					TOTAL (SF)
	Northeast Campus	Main Campus (West)	Main Campus (East)	South Campus	Centennial Campus	
RECREATION	0	34,251	521,208	0	0	555,459
ACTIVITIES	69,041	0	437,790	100,445	1,412	608,688
PARKING	437,085	0	1,041,088	1,055	772,663	2,251,891
RESEARCH/	2,673,239	8,238	686,381	127,049	1,683,314	5,178,221

Classroom						
Business	6,009	0	57,853	35,097	430,330	529,289
Library	324,750	0	0	0	243,559	568,309
Housing	208,634	768,823	1,150,705	314,239	478,320	2,920,721
Dining	16,751	0	61,502	0	0	78,253
Management	235,572	150,780	115,957	214,968	124,741	842,018
Health	0	0	69,345	0	0	69,345
Facility	80,854	271,842	39,146	11,550	46,080	449,472

b. Travel Distance Calculation

To control the influence of road network to travel accessibility, we calculate building accessibility for both Euclidean distance and network distance. In this study, the Euclidean distance is measured by the straight-line distance between two building centroids in Euclidean space. Network distance refers to the real distance between two points along the road network. In an ideal model, network distance varies as transportation mode change. Parker and Vanderslice (2011) studied the pedestrian network generation using road center lines as a basis. Van Eggermond and Erath (2016) used the offset network with additional data sources to generate pedestrian networks. With the limitations of the data sources, this study uses an identical network for walking and biking. One of the characteristics of EcoPRT is that it could operate on sidewalks, thus EcoPRT uses the same network as walking and biking.

The road network data is drawn from Wake County Open Data website (2017). Total distance for each trip is calculated by measuring the door to door distance. The total distance includes both the distance from geometry centroids of origin and destination buildings to the closest road on the network as well as the shortest network distance between these points.

Buses operate on scheduled routes. This means the shortest network distance is not applicable in transit distance calculation. Travelers may choose different bus stops and routes even if they go to the same place. To control those factors, we designate five bus stops for the study area (see

Exhibit **40**). We assign one bus stop with the highest ridership to each of the five parcels. We assume all trips start at 9:00 am on a weekday. For those trips which have several routes available, bus route selection is determined by the earliest arriving time. Transfer distances are measured by the building centroid to the bus stop in each parcel. Overall, a complete trip consists of the walking distance from origin point to the bus stop at the parcel, headway distance from the on-board stop to the off-board stop, and the walking distance from the off-board stop to the destination point. As noted in study limitations, transit likely performs worse in this model than in reality due to long transfer distances as a result of one stop per parcel.

c. Travel time calculation

Transit times are collected from the Wolfline operating schedule. In addition to headway time and transfer time, the study also adds average wait time to the model to account for random arrival and service variability. We use one-quarter of the headway time as the wait time for each trip given that by pure randomness an average rider would wait for one-half the headway. With the proliferation at NCSU of real-time mobile phone apps, like TransLoc, it is assumed that wait times are non-random. For a complete bus trip, the total time use would be the sum of travel time between the origin and destination parcels, wait time, and headway time. Travel time for walking and biking are calculated using the function of distance over speed - we use 3.1 miles per hour for walking speed and 9.6 miles for biking speed.

d. Accessibility Calculation for Each Transportation Mode.

In this study, accessibility is measured by the total other-building square footage that a building can access. Access decreases as the total square footage decreases or the time duration increases. Accessibility for each mode is calculated by the function below:

$$A_i = \sum_{j=1}^{n} S_j e^{at_{ij}}$$

Where $\mathbf{A}_i$ is the accessibility for building i, $\mathbf{S}_j$ is the gross square footage at attraction building j, **a** is the impedance factor; $\mathbf{t}_{ij}$ is the total travel time from trip production to trip attraction. In this function, we use -0.2 as the impedance factor in the consideration of the influences of traffic congestion and light phasing along Western Boulevard, Varsity Drive, and the rail road next to Yarbrough Drive. This impedance factor is based on a large scale agent-based survey in 2012 (Huegy, 2015). Other factors that may affect accessibility include: campus land use, time of day and topography.

We limit the maximum Euclidean distance for walking as 1-mile, the longest distance that a pedestrian can reach during a class break of 20 minutes. We calculate both the accessibility for Euclidian distance within 1-mile buffer and network distance within 1-mile road distance. Bike and transit can access most of the study region within 20 minutes; no distance restrictions are made for those modes. Thus, we assume that trips happen between any two buildings for bike and transit but are spatially bound for walking.

e. Calculating total area accessibility

This study focuses on trips made by students for cross campus travel. The total accessibility is calculated by the function below:

$$A = A_{walk} + A_{bike} + A_{transit}$$

Where A is the total accessibility for each building in the study region; A_{walk}, A_{bike}, and $A_{transit}$ represent the value of accessibility for walk, bike and transit, respectively. In this study, we compare the accessibilities for Euclidean distance and network distance and the total accessibilities of different building use.

2.3 Mobility Calculation

To identify the mobility for each travel mode by distance, the study selected four basic mode choices and compared them on total time use. EcoPRT's technical specifications were inputted into the model to simulate its performance.

We calculate the travel time between each pair of stops in both directions. Travel information is recorded for each trip, and total trips occurring between these routes sum up to 100. The study assumes that wait time for transit is 4.5 minutes, which is a quarter of the average transit time; wait time for EcoPRT is 2.5 minutes; wait time for auto is 2.5 minutes, and wait time for bike is 1 minutes (for locking/unlocking the bike).

EcoPRT's average speed is assumed to be 10 miles per hour, based on the technical specification on Phase 1 - Prototype Test in 2017

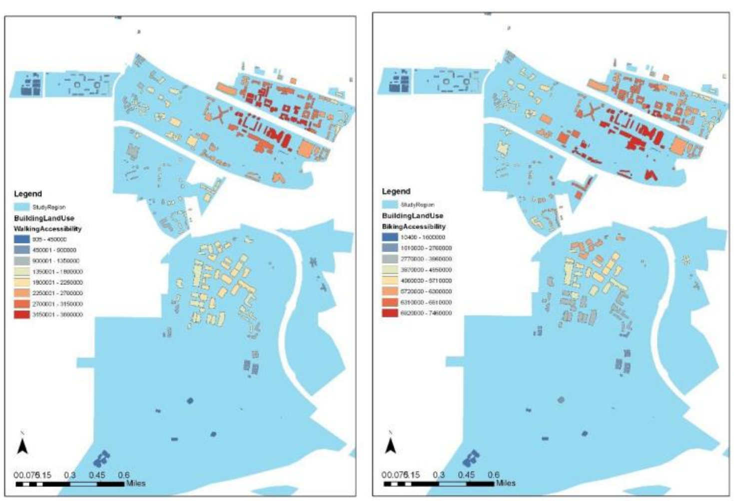
5.5 Results

5.5.1 Euclidean Distance Accessibility

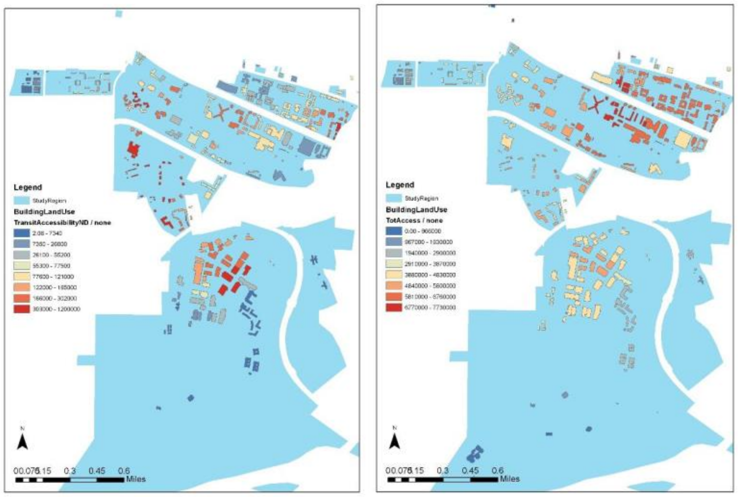
In the calculation of Euclidean distance accessibility, the floor area ratio (FAR) in a region is the most important indicator for walking accessibility. In addition to FAR, building location in the study area also influences accessibility; in other words the more square footage in an area and the closer that square footage is, the higher the accessibility. The most accessible zone at NCSU for walking is North Campus.

Accessibility for almost all buildings improve when shifting the transportation mode from walk to bike, as biking generally increases the number of destinations easily reachable, here calculated by square footage. Exhibit 42 shows the accessibility measures for walking, biking, transit, and all modes. The median value for biking accessibility (4,960,000 SF) is approximately 2.75 times of walking accessibility (1,800,000 SF), meaning that biking increases accessibility to campus destinations by 2.75 times. Buildings along Campus Drive in Centennial Campus increase their accessibility more than three times. The Avent Ferry Residence Hall on South Campus also has an above-average increase. As a result, biking may be a preferable choice over walking in those zones. Although the accessibilities for Wolf Village Apartments and ES King Village Apartments increase, these increases are not as sizeable as the apartments on South Campus as a sizeable amount of destination is within easy walking distance. The Wolf Ridge Apartments have the smallest increase. Students who live in this region would not substantially benefit from a mode shift.

Exhibit 42: Accessibility by Mode and Measure



(a) Euclidean-based walking accessibility (b) Euclidean-based biking accessibility



(c) Network-based transit accessibility (d) Network-based all mode accessibility

Results for biking accessibility show a more centralized pattern compared with walking. Main Campus is the most accessible place among all five zones; Carmichael Gymnasium, Talley Student Union, Tucker Residence Hall, and Jordan Hall have the highest accessible square footage. With a higher speed of cross campus travel, students have access to more places by bike. The accessible center shift indicates that it would be easier for a cyclist to get to NE Campus as well as Centennial Campus. This more centralized accessibility pattern also influences Centennial Campus, as the Engineering Oval is no longer the accessibility center. Instead, buildings which are closer to the Main Campus become the most accessible places. Transportation mode shift not only changes the total accessible square footage, but also changes the accessibility relationship between buildings and zones.

5.5.2 Network-Based Total Accessibility

Total accessibility for the study area is shown on Exhibit 42d. The total accessibility is the sum of accessibility for all modes (walk, bike, transit). Different parcels show different accessibilities. Northeast Campus has the largest accessible square footage. The aggregate square footage for buildings in Northeast Campus are greater than 4,840,000 SF. Although Northeast Campus seems to be the most accessible campus on average, Main Campus East has individual buildings with the highest accessibilities. Bragaw Residence Hall, Tucker Residence Hall, and Student Health Center have over 6,770,000 square footage of accessible area. Students who live in those areas have greater accessibility than other residential places.

The total accessibility map also shows several important corridors among and between campuses. Dan Allen Drive connects Northeast Campus and Main Campus East. Buildings adjacent to this corridor have varying uses, including commercial, education, parking, recreation, activity, residence, etc. With convenient bus routes and good infrastructures for walking, biking, and driving, this corridor becomes the most accessible area in the study region. Cates Avenue intersects with Dan Allen Drive and most buildings in the Main Campus East sit along the two bounds of the road. Finally, Varsity Drive is the longest corridor in the study area, going through Main, South Campus, and Centennial Campuses. Although this corridor connects a large area west of the study area, the accessibility measure for this corridor is not as high as other corridors.

5.5.3 Network Accessibility Variance Across Travel Modes

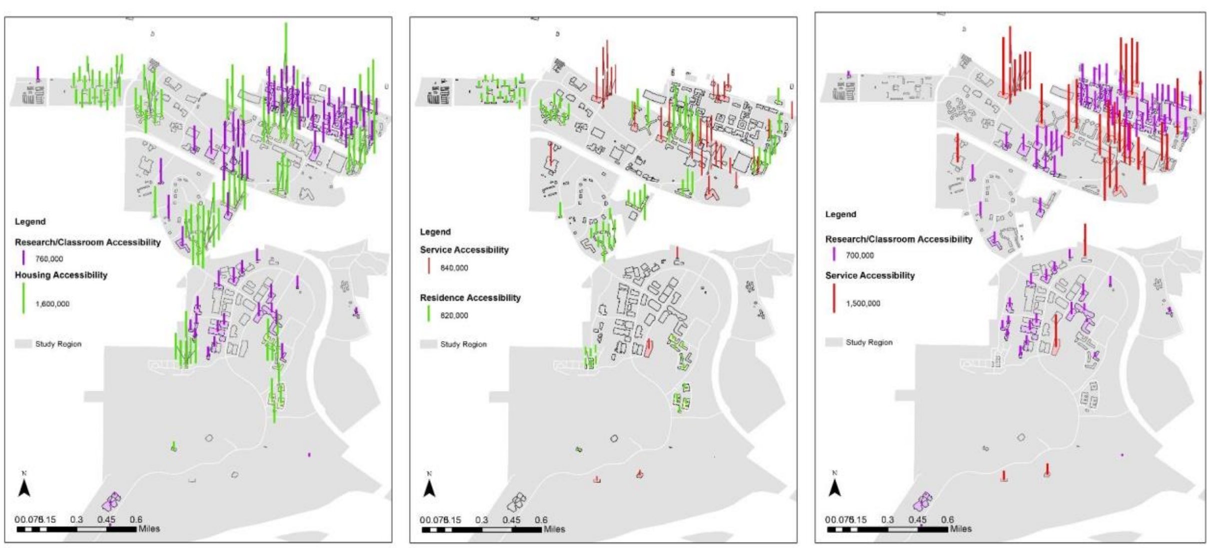
Building network accessibility changes as transportation mode changes. Overall, biking and walking network accessibility indicators are comparable to Euclidean distance results. Biking accessibility is the highest among all the three modes, with walking second highest. Transit accessibility is not as high as walking partly because the transit model limits the possible bus stops. Unlike biking or walking, the most accessible buildings for transit are close to the designated bus stops at each zone. Accessibility decreases as distance increases from the stops. In other words, stop location is an important factor for transit accessibility.

5.5.4 Network Accessibility Variance Across Building Uses and Trip Purpose

Trip purpose and building use influences building accessibilities. This study focuses on three origin-destination categories: 1) trips between residences and research/classrooms; 2) trips between residences and service destinations; and 3) trips between service destinations and research/classrooms. Each category has two trips but the OD calculations are the same.

Trips between residence and research/classroom mainly refer to two trip purposes: going to school and going back home. Results are shown in Exhibit 43a, where higher bars show greater accessibility at that location for the mode in question. The average accessible square footage for residential buildings is 1,600,000 SF, which is the highest among all building uses. Interestingly, accessibility in the opposite direction is far less square footage on average (mean value for the accessibility from research to residence is 760,000 SF). Research buildings on Centennial Campus have lower accessibility than other campuses because most of the on-campus apartments are away from the Centennial Campus except for the Campus Shore Apartments and Wolf Ridge Apartments.

Exhibit 43: Network-based accessibility for different trip purposes



(a) Trips between residence and research buildings

(b) Trips between residence and service buildings

(c) Trips between service and research buildings

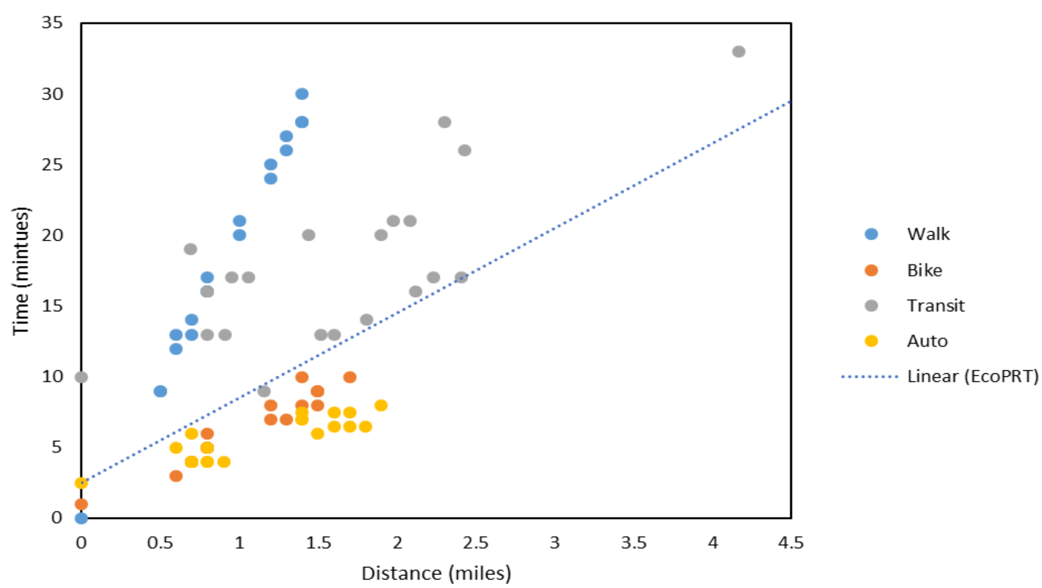
Accessibility for residence-service trips are shown on Exhibit 43b. The results support the concept that an accessibility gap exists at the Centennial Campus, with apartments there having the lowest accessibility to service buildings. Two factors may contribute to this. One is that Centennial Campus has relatively few service buildings. The total square footage for the James Hunt Library is not comparable with the total service area of Main Campus or Northeast Campus. Another reason is that network distances from apartments on Centennial Campus to Main Campus service buildings are longer than other campuses. Students must make choices between traveling short distance for limited services or traveling long distance for more services. Service buildings on Main Campus East have much better access to apartments because travel distances are shorter and apartment areas larger.

Accessibilities for trips between service buildings and research buildings are higher than average on Centennial Campus (Exhibit 43c). However, overall, accessibility from research buildings to service buildings are low. Of note, Hill Library on Main Campus has a relatively higher accessibility than Hunt Library on Centennial Campus.

5.5.5 Mobility

As distance increases, time travel by mode is not the same (Exhibit 44). Average walking time is 10.5 minutes, which is the highest among all modes. Wolfline Transit is about 1.75 minutes fewer than walking. Biking is the fastest mode between 0.5 to 1.5 miles. When distance rises to 1 to 1.5 miles, walking time soars to 26 minutes, limiting walking as a mobility option. Notably, transit time decreased from 9 minutes to 6.5 minutes as distance increased. Multiple reasons could possibly contribute to this decrease. Restricted by the fixed bus schedules, buses do not necessarily operate on the nearest path. For example, when traveling from Wolf Village to Dan Allen and Witherspoon, buses turn back to the Gorman Street first and then go to Sullivan Drive. This meandering route not only lengthens the distance but also adds more stops to the trip. In addition, the simulation is designed to happen at 9:00 am. Extra wait time at peak hours increases the total travel time. When travel distance increases to 1.5 miles, the Wolfline Transit serves more effectively, and the average time decrease.

Exhibit 44: Travel Time For Different Transportation



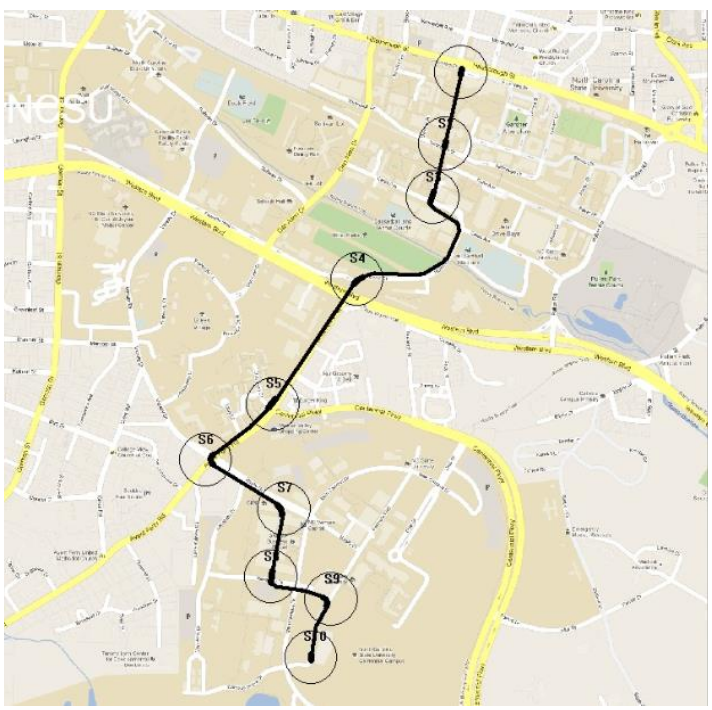
Driving is the most time-saving way among all modes in the distance range from 1.5 to 2 miles. This distance range covers most trips from stop 4 to stop 1, 2, and 3. However, given that the headway time for the biking and driving are almost the same once accounting the 2.5 minutes wait time for driving, biking may be a preferable choice when possible. In contrast, transit requires almost twice as long as driving.

Comparing with other modes, EcoPRT is very competitive in the distance range from 0.5 mile to 1 mile. Because it runs on sidewalks, EcoPRT's routes are the same as pedestrian's routes. With its relatively higher speed than walking and lower wait time than transit, this mode would be an alternative for people who do not ride bicycles. From 1 mile to 1.5 miles, travel time for biking, transit, auto, and EcoPRT are almost the same. All modes achieve good mobility except for walking. As travel time continues increasing, EcoPRT is likely to be faster than transit for some trips and considerably faster than walking. However, the route design advantage for EcoPRT diminishes as network distance increases. Factors like land use, number of crossings, traffic signals, prioritization rules and operating management could affect its transporting efficiency and mode desirability.

5.6 **Reducing Mobility and Accessibility Gaps**

This section highlights some of the mobility and accessibility gaps that exist on the NCSU campus, showing challenges that EcoPRT could potentially address. Centennial Campus, in particular, suffers from a shortage of nearby destinations, as compared to Main and Northeast Campuses. This greatly limits the places that walkers can access and even hinders bicyclists. Transit stands out as the top choice for travelers on Centennial, but while transit remains a good choice across most of NCSU, it cannot be as flexible as walking or biking, modes that can go door-to-door. The goal of EcoPRT is to provide the flexibility of bicycling for those unable (or choosing not to) bicycle, for distances too far to walk, with the speed and convenience of transit. To achieve this the optimum corridor would be anchored on Centennial Campus and would likely travel along the eastern edge of South Campus (e.g., Avent Ferry Road) to pass through Main Campus, up to Northeast Campus, as shown in Exhibit 45.

Exhibit 45: Proposed Route Between Centennial Campus and Main Campus at NCSU



6 Conclusion

At the outset of the project, this research team set off to examine the benefit and application of microtransit, specifically EcoPRT. We sought to understand how microtransit convenience, cost, and usage could play a role in the future of mobility in North Carolina. We started with a preliminary prototype vehicle and went through two vehicle designs, which resulted in building two complete vehicles and the construction of three additional vehicles. We have done some limited pilot testing and have laid the groundwork to continue that effort. Ultimately, we foresee five vehicles operating in a pilot project on Centennial Campus.

In addition to developing and studying the technical aspects of EcoPRT, the research team took a three-pronged approach (user feedback, benefit-cost analysis, and corridor feasibility) to investigate the feasibility of EcoPRT at NCSU, if and when the technological requirements of the vehicle and the system are achieved. Both autonomous vehicles and microtransit are as yet unproven technologies and there are still many questions as to whether they be accepted by the public.

From the focus groups and intercept surveys that were conducted with students, staff, and faculty at NCSU, the research team found a generally positive response to the EcoPRT concept. Students were usually excited by the prospect of being able to ride in an automated vehicle across campus and the flexibility it would afford. While there were some concerns about safety, it is perhaps not surprising that young people would be interested in trying out a new technology. The more important sticking point for many people was about reliability. Students might be willing to risk a little safety, but they really don’t want to take longer to get where they are going; many respondents asked about how long the trips would take compared to the Wolfline buses.

The benefit-cost analysis showed a positive ratio for the system of 4.30 with a 7% discount rate, with a few assumptions. First of all, that by producing EcoPRT vehicles in the hundreds, the cost per vehicle is significantly reduced than what is spent now in the laboratory; one of the unique aspects of EcoPRT is that the components are mostly off-the-shelf technology, making it more reasonable to reach economies of scale and to reduce maintenance costs. The largest monetary assumption was that EcoPRT would allow NCSU to avoid building a large parking garage on the central campus and instead rely on less expensive surface parking on Centennial Campus. This would generate great cost savings, but such a decision would depend upon many factors. However, a demand-responsive, decentralized AMT system like this would certainly increase the utility of more “distant” parking lots.

At the same time, the benefit-cost analysis ignores many other benefits, some of which could be monetized with a dedicated study. The flexibility of an EcoPRT system could greatly increase the mobility of NCSU students, making more destinations accessible, including classrooms, libraries, research facilities, and food. This would improve the overall livability of the students; for instance, some students spoke of choosing courses based upon which campus the classes were held. Furthermore, the university itself could use EcoPRT to help brand NCSU as a technologically advanced, environmentally friendly, innovative place; this would help attract more students as well as private and governmental partners.

Finally, this study investigated how well EcoPRT could close the mobility and accessibility gaps of students on campus. With such a large area broken up into different campuses separated by a major thoroughfare, NCSU has many locations that are not easily accessible by current modal choices. The flexibility of EcoPRT could help serve travelers in these areas, while also feeding transit passengers along Hillsborough St. and Western Blvd. routes.

While this study focused specifically on NCSU, much of the findings could be used to build systems on other North Carolina university campus, as well as a host of other types of locations. Retirement communities, military bases, and business parks are just some examples of where a flexible AMT system could see many benefits. Furthermore, the low-speed nature of EcoPRT may pose fewer safety risks than all-purpose automated vehicles, which could make EcoPRT a good early testbed for these new technologies. In conclusion, EcoPRT and autonomous microtransit, in general, represent promising technologies that are worthy of additional study and consideration as real alternatives to existing mobility solutions. As the technology matures, it could have a real impact in providing a cost effective and convenient means of travel not just in university settings, but also within business campuses, shopping centers, and downtown urban areas.

For future work, we have received a number of inquiries from interested parties who would like to consider a pilot project for EcoPRT when it is deployment ready. Though not deployment ready at the time, further research would help accelerate the development to get the vehicle system to such a readiness level. Such vehicular elements needing additional work include (1) software - integrating the navigation with the obstacle detection (2) network – developing the cloud based fleet management solution, and (3) testing – completing the three phases of the testing protocol as original set forth.

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8 Appendices

Appendix 1
EcoPRT Intercept Survey (English & Spanish)

EcoPRT Survey

Thank you very much for assisting us with this survey. Please circle your chosen answer.

1. Which of the following best describes you?
   a. I am an NCSU student
   b. I work mainly on Centennial Campus (not a student)
   c. I work mainly somewhere else at NCSU (not a student)
   d. I am a visiting student
   e. I am a visiting non-student

2. How do you usually get to campus?
   a. Live on campus
   b. Walk
   c. Personal bike/scooter
   d. Shared bike/scooter
   e. Bus/Wolfline
   f. Your car
   g. Carpool/vanpool
   h. Uber/Lyft/taxi
   i. Not applicable

3. How often do you travel between Main and Centennial Campus?
   a. Daily
   b. 2-3 times per week
   c. Once per week
   d. Monthly
   e. Once a semester
   f. Less than once a semester

4. Which of the following modes do you use for these longer cross-campus trips? Please check all that apply.
   a. Walk
   b. Personal bike/scooter
   c. Shared Bike/Scooter
   d. Bus/Wolfline
   e. Your car
   f. A colleague's car
   g. Uber/Lyft/Taxi
   h. Not applicable

5. Based on initial impressions, what do you like about the EcoPRT concept?

6. What concerns do you have about the EcoPRT concept?

7. How often would you use EcoPRT for future trips across campus?

8. If EcoPRT were an easily available option, how would it affect how often you travel across campus?
   a. I would travel much more frequently
   b. I would travel a little more frequently
   c. I would travel the same amount
   d. I would travel a little less frequently
   e. I would travel much less frequently

9. Considering that EcoPRT will share paths with walkers, bikers, and cars, what speed do you think EcoPRT should travel while on a walking path?
   a. 3 mph (average walking speed)
   b. 7 mph
   c. 10 mph (leisurely biking speed)
   d. 15 mph

10. Considering that existing public transit (Route 8) takes about 20 minutes to travel from Hunt Library to Hill Library, what length of time would be acceptable for an EcoPRT trip?

11. Which of the following pricing models would you be interested in to utilize EcoPRT? Check all that apply:
    a. Student Fees
    b. Pay per Trip
    c. Monthly Subscription
    d. Free

12. What price would you be willing to pay for a campus-to-campus trip?
    a. $1
    b. $2
    c. $3
    d. Other ______________________________

On a scale of one to five, where one is "not at all concerned" and five is "extremely concerned," ...

13. How concerned would you be about safety when taking an EcoPRT trip?

    1 (Not at all concerned) 2 3 4 5 (Extremely concerned)

14. How concerned would you be about reliability (time and availability) when taking an EcoPRT trip?

    1 (Not at all concerned) 2 3 4 5 (Extremely concerned)

15. How concerned would you be about sharing the vehicle with another passenger when taking an EcoPRT trip?

    1 (Not at all concerned) 2 3 4 5 (Extremely concerned)

16. If you were walking and an EcoPRT vehicle was coming towards you, how would you want the vehicle to communicate to you that it was stopping and that you should proceed? Please rank the following choices from 1 (first choice) to 4 (last choice)
    a. ____ Beep or tone
    b. ____ Voice
    c. ____ Video display (e.g., a "walk signal")
    d. ____ Other: ______________________________

Encuesta de EcoPRT

Muchas gracias por ayudarnos con esta encuesta. Por favor, marque la respuesta elegida.

1. ¿Cuál de los siguientes se describe mejor?
   a. Soy un estudiante de NCSU
   b. Trabajo principalmente en el campus centenario (no es un estudiante)
   c. Trabajo principalmente en otro lugar en NCSU (no es un estudiante)
   d. Soy estudiante visitante
   e. Soy un visitante

2. ¿Cómo sueles llegar al campus?
   a. Vivo en el campus
   b. Caminar
   c. Bicleta personal/scooter
   d. Bicleta compartida/scooter
   e. Autobús/Wolfline
   f. Su coche
   g. Carpool/vanpool
   h. Uber/Lyft/taxi
   i. No aplicable

3. ¿Con qué frecuencia viaja entre "Main Campus" y "Centennial Campus"?
   a. Diario
   b. 2-3 veces per semana
   c. Una vez por semana
   d. Mensual
   e. Una vez al semestre
   f. Menos de una vez al semestre

4. ¿Cuál de los siguientes modos usted utiliza para estos viajes más largos entre campus? Por favor marque todos los que apliquen.
   a. Caminar
   b. Bicleta personal/scooter
   c. Bicleta compartida/scooter
   d. Autobús/Wolfline
   e. Su coche
   f. Carpool/vanpool
   g. Uber/Lyft/taxi
   h. No aplicable

5. Basado en impresiones iniciales, ¿qué te gusta del concepto EcoPRT?

6. ¿Qué preocupaciones tiene sobre el concepto EcoPRT?

7. ¿Con qué frecuencia usaría EcoPRT para futuros viajes por el campus??

8. Si EcoPRT fuera una opción fácilmente disponible, ¿cómo afectaría la frecuencia con la que viajas por el campus?
   a. Viajaría mucho más frecuentemente
   b. Viajaría un poco más con frecuentemente
   c.
   d. Viajaría la misma cantidad
   e. Viajaría un poco menos con frecuencia
   . Viajaría mucho menos con frecuencia

9. Teniendo en cuenta que EcoPRT compartirá los caminos con los caminantes, ciclistas y coches, ¿qué velocidad crees que EcoPRT debe viajar mientras que en un camino a pie?
   a. 3 mph (velocidad media de caminar)
   b. 7 mph
   c. 10 mph (velocidad de ciclismo pausado)
   d. 15 mph

10. Considerando que el transporte público existente (Ruta 8) tarda unos 20 minutos en viajar de Hunt Library a Hill Library, ¿qué tiempo sería aceptable para un viaje EcoPRT?

11. ¿Cuál de los siguientes modelos de precios estaría interesado en utilizar EcoPRT? Marque todos los que apliquen:
   a. Cuotas estudiantiles
   b. Pago por viaje
   c. Suscripción mensual
   d. Libre

12. What price would you be willing to pay for a campus-to-campus trip?
   a. $1
   b. $2
   c. $3
   . Otros ____

En una escala de uno a cinco, donde uno es "no está preocupado" y cinco está "muy preocupado", ...

13. ¿Qué tan preocupado estaría usted acerca de la seguridad al tomar un viaje EcoPRT?

   1 (No está preocupado) 2 3 4 5 (Muy preocupado)

14. How concerned would you be about reliability (time and availability) when taking an EcoPRT trip?

   1 (No está preocupado) 2 3 4 5 (Muy preocupado)

15. How concerned would you be about sharing the vehicle with another passenger when taking an EcoPRT trip?

   1 (No está preocupado) 2 3 4 5 (Muy preocupado)

16. Si estabas caminando y un vehículo EcoPRT venía hacia ti, ¿cómo querrías que el vehículo te comunicara que se estaba deteniendo y que debías proceder? Por favor, alinee las siguientes opciones de 1 (primera opción) a 4 (última opción)
   a. ____ Pitido o tono
   b. ____ Voz
   c. ____ Visualización de vídeo (e.g., un "señal de la caminata")
   d. ____ Otros: ____

Appendix 2
EcoPRT Intercept Survey Results

Which of the following best describes you?		
NCSU Student	63	84%
CC Staff	10	13%
Non-CC Staff	0	0%
Other Student	2	3%
Other	1	1%
	76	
How do you usually get to campus?		
Live on campus	22	29%
Walk	13	17%
Personal Bike/Scooter	4	5%
Bus	19	25%
Personal Car	23	31%
Pool	0	0%
Shared B/S	0	0%
TNC	0	0%
N/A	0	0%
	81	100%
How often do you travel between Main and Centennial Campuses?		
Daily	26	34.7%
2-3/wk	30	40.0%
1/wk	6	8.0%
Monthly	7	9.3%
Semester	1	1.3%
<Semester	5	6.7%
	75	100%
Which of the following modes do you use for these longer cross-campus trips?		
Walk	14	19%
Personal Bicycle/ Scooter	14	19%
Shared Bicycle/ Scooter	9	12%
Bus	53	71%
Personal Car	20	27%
Other Car	4	5%
Ridehailing Service	3	4%
N/A	0	0%
75	117	156.0%

If EcoPRT were an easily available option, how would it affect how often you travel across campus?		
Much More	12	20.0%
Little More	19	31.7%
Same	29	48.3%
Little Less	0	0%
Much Less	0	0%
	60	100%
Considering that EcoPRT will share paths with walkers, bikers, and cars, what speed do you think EcoPRT should travel while on a walking path?		
3 mph	5	9%
7 mph	9	16%
10 mph	29	51%
15 mph	14	25%
	57	100%
Considering that existing public transit (Route 8) takes about 20 minutes to travel from Hunt Library to Hill Library, what length of time would be acceptable for an EcoPRT trip?		
Average	14.4 minutes	
Median	12.5 Min	
Which of the following pricing models would you be interested in to utilize EcoPRT? Check all that apply:		
Student Fees	22	37.3%
Pay per Trip	22	37.3%
Monthly Subscription	5	8.5%
Free	46	78.0%
	59	161.0%
What price would you be willing to pay for a campus-to-campus trip?		
$1	22	37%
$2	20	34%
$3	5	8%
<$1	12	20%
	59	100%

On a scale of one to five, where one is "not at all concerned" and five is "extremely concerned, how concerned would you be about _______ when taking an EcoPRT trip?

	Not at All Concerned	Slightly Conc	Somewhat Concerned	Moderately Concerned	Extremely Concerned	
Safety	3	13	15	18	10	59
Reliability	1	7	11	17	23	59
Sharing	15	16	17	7	4	59
Safety	5.1%	22.0%	25.4%	30.5%	16.9%	100%
Reliability	1.7%	11.9%	18.6%	28.8%	39.0%	100%
Sharing	25.4%	27.1%	28.8%	11.9%	6.8%	100%

If you were walking and an EcoPRT vehicle was coming towards you, how would you want the vehicle to communicate to you that it was stopping and that you should proceed? Please rank the following choices from 1 (first choice) to 4 (last choice)

	1st	2nd	3rd	4th	56 total
Beep or Tone	27	11	11	0	
Voice	13	15	18	1	
Video	19	14	10	1	
Other	3	2	0	6	
Beep or Tone	48%	20%	20%	0%	
Voice	23%	27%	32%	2%	
Video	34%	25%	18%	2%	
Other	5%	4%	0%	11%	

Appendix 3
Benefit-Cost Analysis: Itemized Costs

Year	Value of Time Savings		
	Undiscounted	3% Discount Rate	7% Discount Rate
2020	$2,505,146	$2,505,146	$2,505,146
2021	$2,555,249	$2,480,891	$2,388,136
2022	$2,605,464	$2,455,910	$2,275,612
2023	$2,655,793	$2,430,316	$2,167,924
2024	$2,706,238	$2,404,492	$2,064,589
2025	$2,756,801	$2,378,017	$1,965,599
2026	$2,807,486	$2,351,269	$1,870,628
2027	$2,858,294	$2,324,079	$1,779,860
2028	$2,909,228	$2,296,545	$1,693,171
2029	$2,960,290	$2,268,767	$1,610,102
2030	$3,011,484	$2,240,845	$1,530,737
2031	$3,062,811	$2,212,574	$1,455,141
2032	$3,114,274	$2,184,352	$1,382,738
2033	$3,165,876	$2,155,962	$1,313,839
2034	$3,217,620	$2,127,169	$1,247,793
2035	$3,269,509	$2,098,698	$1,184,870
2036	$3,321,545	$2,069,987	$1,125,007
2037	$3,373,731	$1,703,734	$1,068,123
2038	$3,426,071	$2,012,474	$1,013,774
2039	$3,478,568	$1,983,827	$961,824
2040	$3,531,224	$1,955,239	$912,468
2041	$3,584,043	$1,926,423	$865,546
2042	$3,637,028	$1,898,165	$820,877
2043	$3,690,183	$1,869,816	$778,260
2044	$3,743,510	$1,841,433	$737,846
2045	$3,797,014	$1,813,454	$699,410
2046	$3,850,697	$1,785,568	$663,090
2047	$3,904,564	$1,757,835	$628,244
2048	$3,958,618	$1,730,312	$595,376
2049	$4,012,863	$1,702,658	$564,208
2050	$4,067,302	$1,675,728	$534,443
2051	$4,121,940	$1,648,776	$537,089
Total	**$105,660,463**	**$66,290,459**	**$40,941,471**

Year	Vehicle Operating Cost Savings		
	Undiscounted	**3% Discount Rate**	**7% Discount Rate**
2020	$108,422	$108,422	$108,422
2021	$110,590	$107,372	$103,358
2022	$112,768	$106,295	$98,492
2023	$114,956	$105,196	$93,839
2024	$117,154	$104,091	$89,377
2025	$119,362	$102,962	$85,105
2026	$121,581	$101,824	$81,009
2027	$123,810	$100,670	$77,096
2028	$126,050	$99,504	$73,361
2029	$128,301	$98,330	$69,783
2030	$130,563	$97,152	$66,365
2031	$132,837	$95,961	$63,111
2032	$135,122	$94,775	$59,994
2033	$137,420	$93,583	$57,029
2034	$139,729	$92,375	$54,187
2035	$142,051	$91,183	$51,479
2036	$144,386	$89,981	$48,904
2037	$146,734	$74,101	$46,456
2038	$149,095	$87,578	$44,117
2039	$151,469	$86,383	$41,881
2040	$153,857	$85,191	$39,757
2041	$156,260	$83,990	$37,737
2042	$158,676	$82,813	$35,813
2043	$161,107	$81,633	$33,977
2044	$163,553	$80,452	$32,236
2045	$166,014	$79,288	$30,580
2046	$168,490	$78,129	$29,014
2047	$170,983	$76,976	$27,511
2048	$173,491	$75,833	$26,093
2049	$176,016	$74,684	$24,748
2050	$178,558	$73,566	$23,462
2051	$181,116	$72,446	$23,599
Total	**$4,600,522**	**$2,882,739**	**$1,777,894**

Year	Safety Benefits		
	Undiscounted	3% Discount Rate	7% Discount Rate
2020	$20,278	$20,278	$20,278
2021	$20,684	$20,082	$19,331
2022	$21,090	$19,879	$18,420
2023	$21,496	$19,671	$17,547
2024	$21,902	$19,460	$16,709
2025	$22,309	$19,244	$15,906
2026	$22,716	$19,025	$15,136
2027	$23,124	$18,802	$14,399
2028	$23,532	$18,576	$13,695
2029	$23,940	$18,348	$13,021
2030	$24,348	$18,118	$12,376
2031	$24,757	$17,885	$11,762
2032	$25,167	$17,652	$11,174
2033	$25,576	$17,417	$10,614
2034	$25,986	$17,180	$10,077
2035	$26,397	$16,944	$9,566
2036	$26,808	$16,706	$9,080
2037	$27,219	$13,746	$8,617
2038	$27,630	$16,230	$8,176
2039	$28,043	$15,993	$7,754
2040	$28,455	$15,756	$7,353
2041	$28,868	$15,517	$6,972
2042	$29,282	$15,282	$6,609
2043	$29,695	$15,047	$6,263
2044	$30,110	$14,811	$5,935
2045	$30,525	$14,579	$5,623
2046	$30,940	$14,347	$5,328
2047	$31,356	$14,116	$5,045
2048	$31,772	$13,888	$4,779
2049	$32,189	$13,658	$4,526
2050	$32,606	$13,434	$4,284
2051	$33,024	$13,210	$4,303
Total	**$851,824**	**$534,878**	**$330,659**

Year	Parking Cost Savings		
	Undiscounted	3% Discount Rate	7% Discount Rate
2020	$29,255,040	$29,255,040	$29,255,040
2021	$960,000	$932,064	$897,216
2022	$984,000	$927,518	$859,426
2023	$1,008,600	$922,970	$823,320
2024	$1,033,815	$918,545	$788,697
2025	$1,059,660	$914,063	$755,538
2026	$1,086,152	$909,652	$723,703
2027	$1,113,306	$905,229	$693,255
2028	$1,141,138	$900,815	$664,143
2029	$1,169,667	$896,433	$636,182
2030	$1,198,908	$892,108	$609,405
2031	$1,228,881	$887,744	$583,841
2032	$1,259,603	$883,486	$559,264
2033	$1,291,093	$879,235	$535,804
2034	$1,323,371	$874,880	$513,203
2035	$1,356,455	$870,708	$491,579
2036	$1,390,366	$866,476	$470,917
2037	$1,425,125	$719,688	$451,195
2038	$1,460,754	$858,047	$432,237
2039	$1,497,272	$853,894	$413,996
2040	$1,534,704	$849,766	$396,568
2041	$1,573,072	$845,526	$379,897
2042	$1,612,399	$841,511	$363,918
2043	$1,652,709	$837,427	$348,556
2044	$1,694,026	$833,292	$333,893
2045	$1,736,377	$829,294	$319,841
2046	$1,779,786	$825,287	$306,479
2047	$1,824,281	$821,291	$293,527
2048	$1,869,888	$817,328	$281,231
2049	$1,916,635	$813,228	$269,479
2050	$1,964,551	$809,395	$258,142
2051	$2,013,665	$805,466	$262,381
Total	**$73,415,300**	**$55,997,405**	**$44,971,872**