

**DESIGNING A PERSONAL RAPID TRANSIT SYSTEM FOR THE
UNIVERSITY OF DELAWARE BASED ON STUDENT SCHEDULE DATA**

by

Yun Tang

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Civil Engineering

Summer 2019

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ABSTRACT

Personal Rapid Transit (PRT) system is an automatic guided rail transit system that is used for urban area transportation and is designed to provide uninterrupted transportation on demand. This paper aims to provide a reasonable case study of developing a campus PRT system. This research using VISSIM operate the traffic simulation based on students' trip distribution data and then with the help of MATLAB analyzing the simulation data, the logical blueprint of the PRT system around the University of Delaware, including guideway network and operation scheme.

This paper focuses on the planning and adjustment of the PRT network. Recommendations for the future study include completing the implementation plan of the construction according to the local geological and hydrological conditions, and the potential negative impact of the PRT system on surrounding areas.

Chapter 1

INTRODUCTION

1.1 Motivation

The first Personal Rapid Transit (PRT) system in the United States was built in the 1970's. Since this pilot project, no other systems like it have been installed anywhere in the US. Since 2000, other PRT systems have been built around the world, but most are very small and would likely be classified as demonstrations. Considering the advantages they have over traditional transit systems, such as service on demand and higher occupancy rates, and new technologies such as fuel cells and wireless information networks, it is not obvious why more PRT systems are not being built. This research will provide a background of PRT and propose a system design for use at the University of Delaware.

1.2 Objectives

This paper provides the general process of designing a PRT system based on student data. Data from student schedules were converted into hourly Origin-Destination (OD) matrices. These matrices combined with the geography of the University of Delaware were used to design a PRT system. The primary objective of the research is to provide a reasonable operating plan and network design for the University of Delaware (UD) PRT system.

1.3 Methodology

This research includes a review of the available literature on PRT and transit systems as well as current experiences. Current system designs, both domestic and abroad, were also investigated to serve as frameworks for the proposed UD design. Based on the service to be provided, routes were developed for the PRT system and an investigation was done as to the location of stations, the number of vehicles needed and headways to provides satisfactory service to users.

1.4 Outline

Chapter 1 introduces the motivation and determination of this paper. Chapter 2 introduces the relevant literature review about the PRT system. Chapter 3 introduces the process of design of the UD PRT system. Chapter 4 using MATLAB discusses the process and data analysis of the VISSIM simulation of the UD PRT system. Chapter 5 provides suggestions for further study.

Chapter 2

LITERATURE REVIEW

2.1 PRT System Overview

2.1.1 History

The history of PRT traces back to the inventions of Donn Fichter in 1953 (J. E. Anderson, 1996). His Veyar system is the first PRT-like system. Early publications include the book, *Individualized Automated Transit and the City*, written by Fichter in 1964 which included all the essential elements for PRT system.

One method to track the historical developmental of PRT is through bibliometrics. Bibliometrics is a statistical analysis of written publications, such as book or articles, for a specific topic. As shown in Figure 2-1, PRT publications peaked between 1971 and 1975. This is in large part attributable to U.S. Department of Housing and Urban Development (HUD) studies from the mid-1960s. Interestingly, the number of publications of PRT dropped sharply during the 1980s after the Morgantown PRT went operational. PRT publication have continued to show slow but steady growth from the 80's to today.

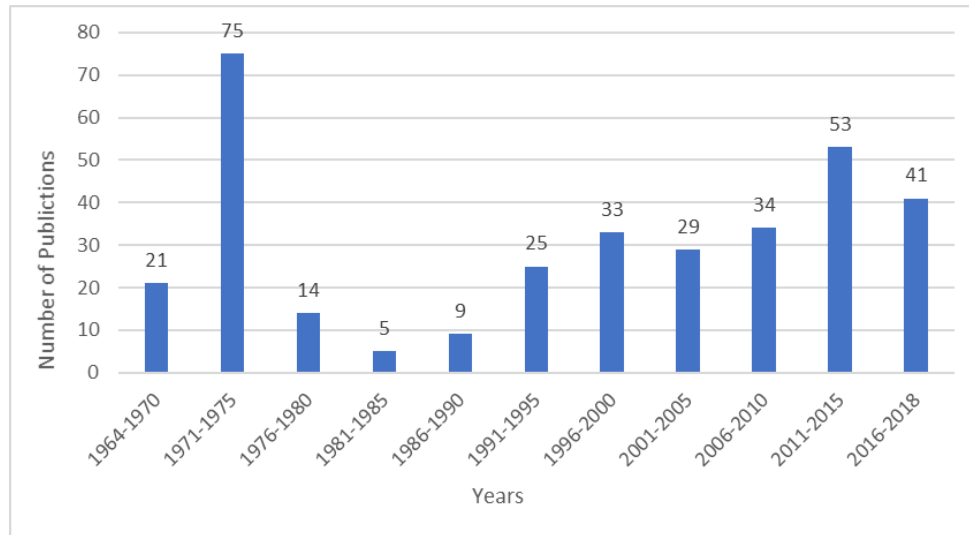


Figure 2-1 Trend in PRT Publication Activity

PRT system trials and testing can also be used as a measure of PRT activity. The German firm DEMAG+MBB, inspired by HUD studies, began developing and testing the Cabintaxi system from 1969 to 1980. Japan tested the Computer-Controlled Vehicle System (CVS) program from 1970 to 1978. The Morgantown PRT went operational in 1975 and continues in operation today. In the 1990s, Raytheon invested heavily in PRT 2000, a PRT system based on technology developed by J. E. Anderson at the University of Minnesota (Samuel, 1999).

New research in PRT has been occurring since 2000. In 2001, the European Commission Directorate-General Research appropriated \$3.5 million toward a 30-month PRT program called “Evaluation and Demonstration of Innovative City Transport” (EDICT) to analyze and apply PRT in different urban environments (Carnegie & Hoffman, 2007). A company named 2getthere built CyberCab in the Netherlands in 2002 to investigate the public acceptance of PRT-like systems, and then in 2010, an underground 2getthere system with ten vehicles and two stations has

operated at Masdar City, UAE. In May 2011, the Heathrow Airport PRT system, with three stations, went operational. In 2014, the SkyCube PRT system was put into use in Suncheon, South Korea.

2.1.2 Conception and Classification

2.1.2.1 Concept

The term Personal Rapid Transit (PRT) is derived from multiple sources (J. E. Anderson, 2006). As defined by the U.S. Senate Committee on Appropriations' Transportation Subcommittee, PRT is a subclass of Automated Guideway Transit (AGT) systems. AGT has driverless vehicles and exclusive right of way (United States Congress Office of Technology Assessment, 1975). Based on the different service capacity and route type, AGTs are characterized into three main categories: Shuttle-Loop Transit (SLT), Group Rapid Transit (GRT) and PRT.

The Advanced Transit Association (ATRA) has defined PRT as: fully automatic vehicles on a network operating on small guideways that are usually elevated providing continuous door to door service (Dunning & Ford, 2003).

The concept of PRT could be summarized as an automated transportation system consisting of small vehicles and their dedicated working tracks. The PRT system can also be thought of as a new monorail transportation system. It has some of the essential features of the automated people mover (APM) or the automated guideway transit (AGT), but it also has unique door-to-door service characteristics.

2.1.2.2 Classification

There are many ways to classify PRT systems, based on their design, operation, power system, track style, etc. (MacDonald, 2011).

- Capacity – Capacity of any PRT (or any transportation) system is a function of vehicle size, headway, and operating speed. Since PRT systems are on-demand systems, responding to calls for service, they generally have higher occupancy than traditional transit systems. Transit buses serve all routes and stops regardless of number of passengers.
- Power - Generally, PRT systems use electric vehicles. The electricity can be from batteries, fuel cells or via catenary from power lines above or beside the vehicle.
- Guideways - Most PRT have specialized guideways or railways, but a few PRT systems are trackless, for example, the PRT system developed by 2getthere in Masdar City in Abu Dhabi uses a concrete surface with a painted line for guidance.
- Guideway Mode - There are two modes of PRT guideway systems. One is the single mode operating on specialized railways or guideways. Dual model systems can operate with either specialized guideways or can operate on traditional roads. There are two common types of single model: Supported PRT and Suspended PRT. Figure 2-2 ULTra (PRT Consulting Inc, 2015) shows an example of the supported PRT system. The structure of this guideway system is composed of columns, cross members or cantilevers and tracks erected to achieve large spans. The vehicle travels above the track. With suspended systems, the vehicle travels under the track. An example of a suspended PRT system is SkyTran shown in Figure 2-3 (Marlaire, 2009). A hybrid of this is

shown in Figure 2-4 (J. E. Anderson, 1996). In this design, one vehicle is supported in a guideway above the track and one is suspended below. This design could have complicated station designs. An example of dual-mode is shown in Figure 3-5. (Pedersen, 1966). In this case, the vehicle can be operated on the track or the regular city road and is called the staRRcar. It was invented by William L. Aiden and Martin Gilvar. They envisioned a system of these vehicles would combine the mobility of automobiles and the efficiency of rapid-transit systems.



Figure 2-2 ULTra (PRT Consulting Inc, 2015)



Figure 2-3 SkyTran (Marlaire, 2009)

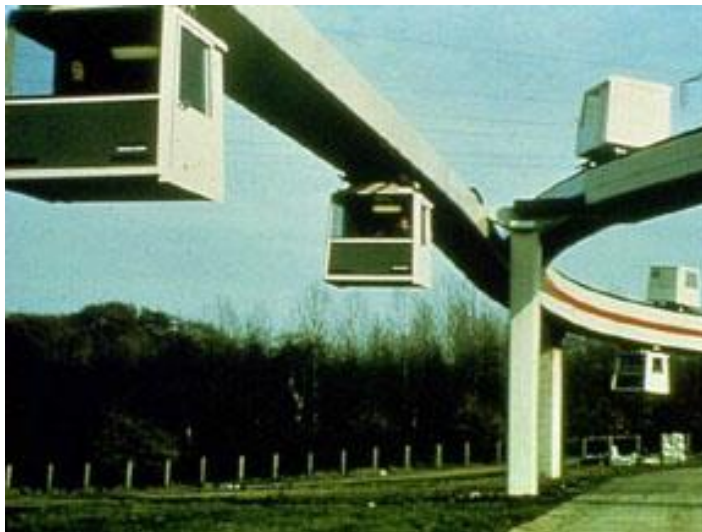


Figure 2-4 Carbinetaxi (J. E. Anderson, 1996)



Figure 2-5 StaRRcar (Pedersen, 1966)

This research used a single model, guideway based system design. It was also envisioned that the guideway system would be elevated which reduces impact on the available right of way for vehicles.

2.1.3 Components

Figure 2-6 demonstrates five main components of the PRT system: control system, propulsion system, vehicle/guideway system, communication system, and operating system. This research is focused on general guideway layout and system operating characteristics. It does not include the structural design of guideway and stations nor the specific technologies used for propulsion, communication or operations.

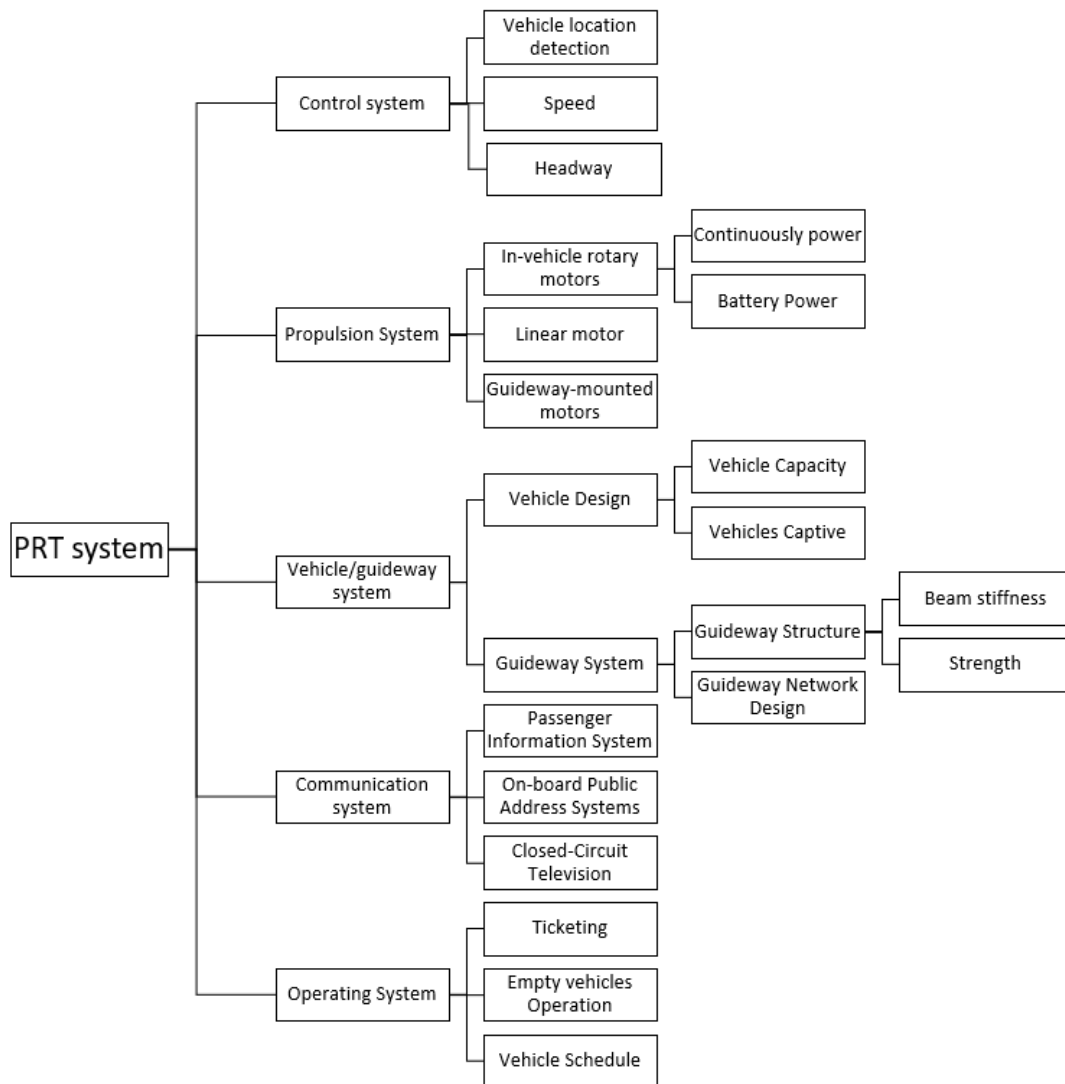


Figure 2-6 PRT System Structure

2.2 PRT System Case Study – West Virginia University Personal Rapid Transit

2.2.1 History

In the late 1960s, West Virginia University was chosen as the location for a pilot PRT system demonstration project. The system was designed to alleviate the

student daily commute burden and reduce traffic congestion. West Virginia University Personal Rapid Transit (WVU PRT) was funded by the Urban Mass Transportation Administration (UMTA) of the U.D Department of Transportation in the early 1970s. WVU PRT was designed to connect three campuses areas and the city's downtown.

WVU PRT was developed from the Alden staRRcar and was built by a consortium led by Boeing Vertol (Sproule & Neumann, 1991). The number of stations increased to five in 1978, and a renewal project was approved in 2012. Also, a new vehicle control system was due to be commissioned in 2018, and the vehicle fleet will also be replaced.

2.2.2 Vehicle

The WVU PRT system contains 73 vehicles. They utilize an automatic remote-control system, and the highest speed is 30 mph. Figure 2-7 (PRT Consulting Inc, 2015) is exterior views of the WVU PRT vehicle. Each vehicle can contain twelve students. These vehicles navigate the guideway autonomously and are also controlled from a central control center.



Figure 2-7 WVU PRT Vehicle

2.2.3 Guideway

In order to connect different campus, WVU PRT system has five stations: Walnut, Beechurst, Engineering, Towers, and Medical, which are shown in Figure 2-8 (Raney & Young, 2005). When the vehicle arrives at the station, the system automatically chooses whether to overlap, cross the station, or stop at the station.

The track consists of a cement and a magnetic coil that feeds back data to the system. Due to snowy weather, heating coils are also buried in the cement track to melt snow. Heating stations are also installed at several stations to heat these agents.

Thirty-five percent of the track of the system is located on the ground plane or below, and the remaining sixty-five percent belongs to the elevated section.

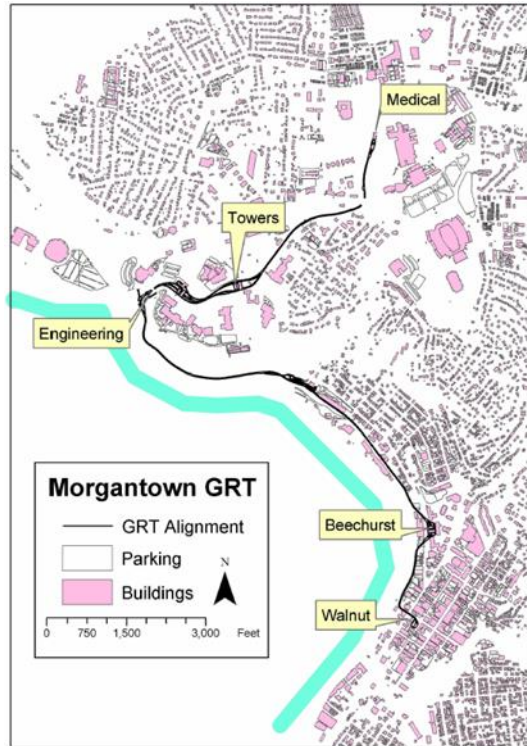


Figure 2-8 MVU PRT Route (Raney & Young, 2005)

2.2.4 Operation Mode

The WVU PRT has three operation modes based on the different traffic supply and demand: demand, schedule, circulation.

During peak hours, the system utilizes schedule mode. If the traffic demand is relatively low, then the system switches to circulation mode, the vehicle number will be reduced, and they will wait at each station.

On the off-peak hour, the system operates in demand mode which is also a “true” PRT mode. The system responds to real-time passenger travel demand. The vehicle will activate if the number of requests reaches fifteen or the wait time exceeds five minutes.

2.3 Summary

There are no technical obstacles for construction of PRT system. The barriers to these systems include operating costs, safety, aesthetics, and public acceptance. While PRT systems are becoming more popular, it is questionable if they will ever be widely deployed. New technologies could be adopted but limited market likely hinders this. The absence of PRT design standards also is a barrier to adoption.

Before PRT goes into commercialization, it must undergo a series of processes such as analysis, preliminary design, prototype development, system design, system testing, and demonstration. All the processes require policy, funding and other aspects of support. Major reasons for past project failures include a lack of funds. The biggest challenge is the cautious investment of PRT construction plans due to budget shortsightedness, the conflicts of laws and regulations, political reasons and engineering or design deficiencies, etc.

Chapter 3

UD PERSONAL RAPID TRANSIT SYSTEM

3.1 Overview

3.1.1 Background

The University of Delaware (UD) is located in Newark, Delaware. Geography and development have resulted in five sub-campuses, referred to as Laird, Central, East, STAR, and South. The campus is just over two miles from north to south and about one mile east to west. Residential and commercial areas exist between Laird and Central and between Central and STAR. This is shown in Figure 3-1.

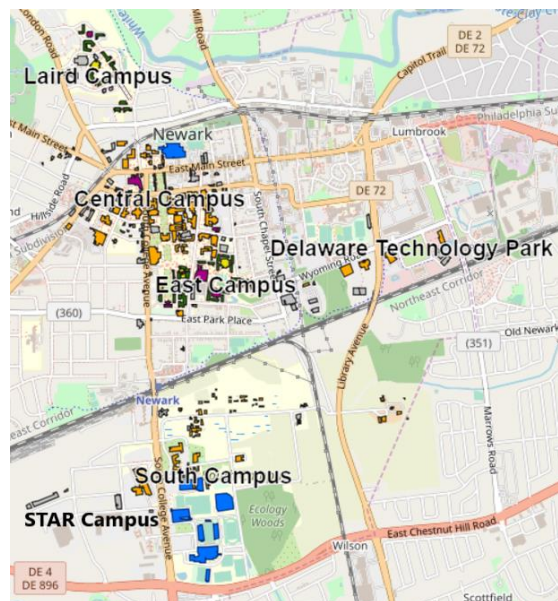


Figure 3-1 UD Campus Map ("Campus Map,")

To improve the efficiency of the daily commute, UD provides five UD Shuttle routes during regular hours, plus an early morning route named EARLY BIRD starting at 4:50 a.m. every weekday.

These five shuttle routes connect all campuses, dormitories and some of the off-campus housing nearby. The different routes are shown below in Figure 3-2 (UD Transportation Services). The UD Shuttle bus system offers students and staff a convenient campus transport method. Based on the 2018 annual report of Parking & Transportation Services, the UD Shuttle has transported more than one million passengers (University of Delaware Facilities & Real Estate & Auxiliary Services, 2018).

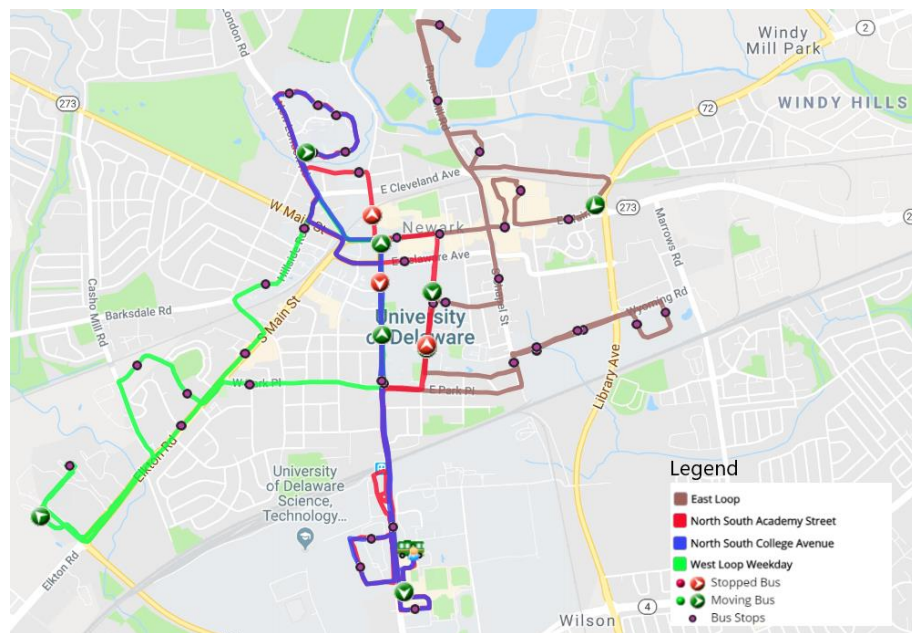


Figure 3-2 UD Shuttle Map (UD Transportation Services)

Although the UD Shuttle bus system helped ameliorate the campus transit condition, it still has some common defects in the traditional public transport system. The traditional bus system has a preset schedule and route that might not fit with real-time traffic demand. Therefore, many commuters may have a long wait time or require secondary transit to arrive at their destination.

The University of Delaware Personal Rapid Transit system (UD PRT) aims to provide a more satisfactory transit system that could reduce the congestion and pedestrian traffic along the Cleveland Ave, E. Main St and Delaware Ave. An expanded elevated PRT system with considerably wider service area and more extended operating hours will also offer more choices of further parking locations, relieving the problem of the campus parking shortage.

3.1.2 Scalability Analysis of UD PRT System

Figure 3-3 (DeIDOT, 2019) demonstrates the traffic condition around the University of Delaware on both peak hour and off-peak hour during weekdays. Streets around the central campus usually have higher volumes of traffic than others. Additionally, many roads that undertake the majority of traffic flow are one-way roads which restrict the capacity of transit volume. In Figure 3-4 (Google Map, 2019), for example, East Main St. is one of the essential roads to travel around central campus; however, the limited width and crosswalks cut down the traffic throughput and increase traffic burden.

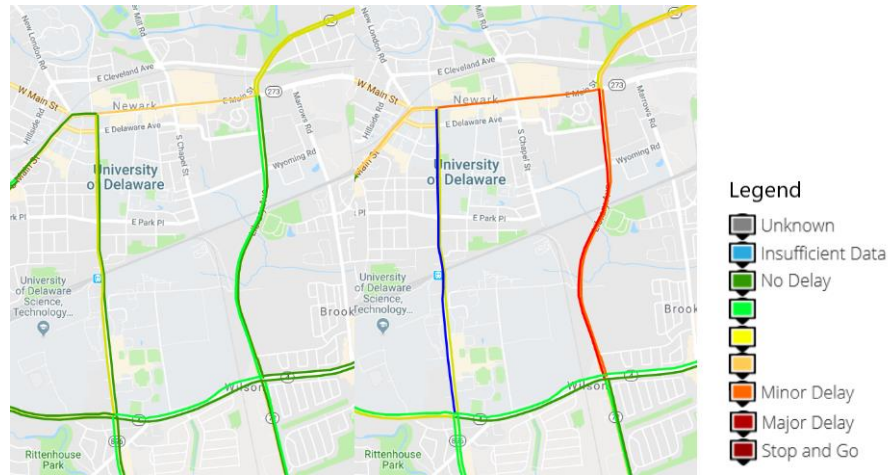


Figure 3-3 UD Traffic Condition (DelDOT, 2019)



Figure 3-4 East Main Street, Newark, DE (Google Map, 2019)

For now, pedestrians, cyclists, motorcyclists, bus drivers, and private vehicle drivers are all clustered on the same road striving for the right of way. The two conventional methods to acclimatize the increasing traffic demand are: widening the existing road or build a new road, but these two methods have many land-uses plans restrictions.

One way to solve this problem might be the UD PRT system. The UD PRT system avoids competing for the right of way with ground traffic in the same horizontal level but develops vertically and has the exclusive right of way by utilizing elevated guideways. Additionally, the width of a single PRT guideway is around eight feet, almost as wide as sidewalks. It has little effect on existing roads and infrastructure, and the ground traffic demand could also be mitigated.

Figure 3-5 (Roland Berger, 2018) is generated based on a report from Roland Berger. The price and convenience of traffic modes are proportional; higher convenience corresponds with higher prices except for the PRT system. It provides high-quality transit service at a reasonable price.

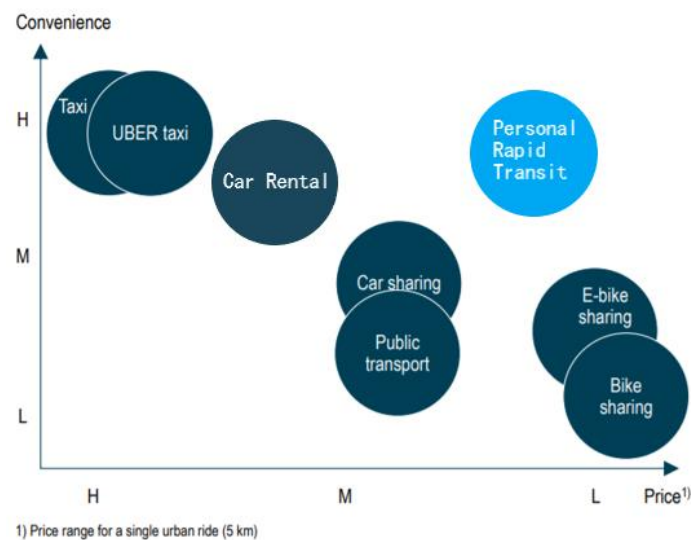


Figure 3-5 Transportation Niche (Roland Berger, 2018)

3.1.3 UD PRT System

The UD PRT system has three service lines: Main line, West-East Campus loop and South campus loop. It is a supported PRT system and utilizes only the track-

guided operational mode. With the UD PRT system located in the city center area, as shown in Figure 3-6, the station design considers one quarter mile as the average distance for the station's service area (passengers will not walk more than a quarter mile to a station).

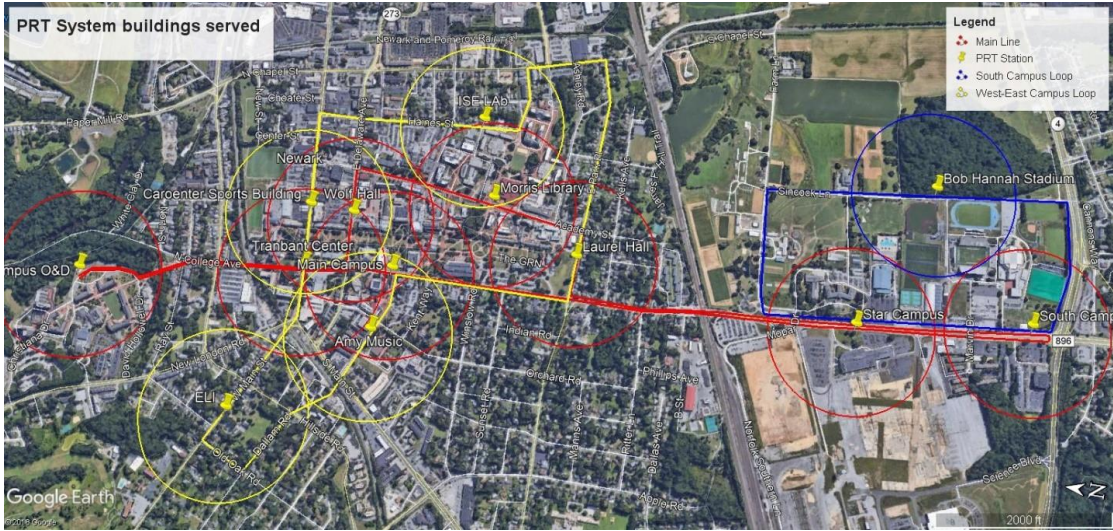


Figure 3-6 UD PRT Servicing Area

The UD PRT system adopts elevated guideways and stations to improve the overall utilization rate of urban space and avoid interference with existing transportation and facilities. The Main Line has eight stations starting from Laird campus, the South campus loop has three stations, and the West-East campus Loop has six stations. Some of the stations are shared by more than one line.

The UD PRT system is similar to the WVU PRT system; it utilizes high volume vehicles (16 passengers) and operates based on two different modes. On peak hour, the operation will follow a preset schedule; on the off-peak hour, the system will

switch to on-demand mode. Once commuters arrive at the station, they can send a travel request. After a control center confirms the request, it will optimize the dispatch of a vehicle to that station.

3.2 Data Requirements and Analysis

3.2.1 Resources

Since the UD PRT system is primarily built for campus commuters, the student schedules from the university will be an appropriate database to estimate demand for student trips on campus. The origin-destination (OD) matrix developed by Benjamin Fisher (Fisher, 2017) provides the framework for verifying the viability of UD PRT system. Data obtained from the University of Delaware includes a list of student class schedules, a record of housing stock and parking availability.

By combining this data, a one-hour OD matrix of student's daily commute itineraries throughout the weekday is generated, forecasting commuter's travel demand on campus during the class exchange periods.

3.2.2 Processing

The original OD matrix developed by Fisher is based on separate buildings on campus, and it needs processing to be implemented in the UD PRT system. The new OD matrix is constructed using the Microsoft Excel software package.

According to the service area of stations, the buildings with travel data are listed, and then the initial OD matrix is summarized into PRT OD matrix with stations as the origin and destination points.

3.2.3 Result

The PRT OD matrix consists of a sixteen by sixteen table picturing a travel pattern between different stations. Originating stations show up in a row, while destination stations are displayed in the column. The cross-section of each row and column represents the travel between two stations. The table is attached as Appendix.

3.3 Guideway Design

3.3.1 Principle

The guideway is the most critical and expensive item in a PRT system (J. E. Anderson, 2009). Anderson brought up thirty-three requirements and nineteen criteria for PRT guideways design: a superior guideway design not only has to follow thoroughly general rules of engineering design but also serve passengers safely, reliably and comfortably in all possible environmental conditions for up to 50 years.

1. Loading criteria: including vertical, lateral design load, longitudinal load, and material stress design
2. Dimensional criteria: including maximum allowable deflection, minimum allowable span, and minimum line headway
3. Sustainable criteria: the minimum system life specified by the Chicago RTA is 50 years; ride quality, and environmental pollution including acoustical noise need to reach ISO standards; the system could manage different expected environments and will be able to be expanded indefinitely.

3.3.2 Methods and Procedures

Although conventional transit technologies cannot directly apply to design a PRT network, some of the network design concepts could be modified to fit the attributes of the PRT system. Figure 3-7 shown general steps of designing a transportation network.

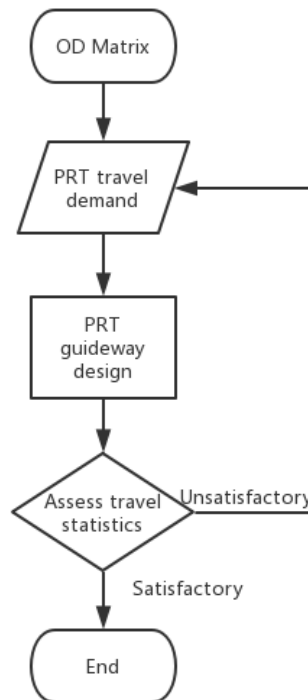


Figure 3-7 Flowchart of PRT Guideway Design

3.3.3 UD PRT Guideway Network Design

3.3.3.1 Route Design

The UD PRT system is composed of one Main Line and two auxiliary lines, a West-East campus loop and a South campus loop, as shown below in Figure 3-8. All guideways are elevated, about sixteen feet above the ground. The main line expands

the passenger's travel distance and shortens the required travel time compared to the existing school shuttle bus system, and the auxiliary lines are built based on the travel demand to provide more personal and flexible travel options. The primary purpose of the Main Line is to rapidly connect Laird Campus, Central Campus, and South Campus. Table 3-1 describes the details of three lines of UD PRT system.

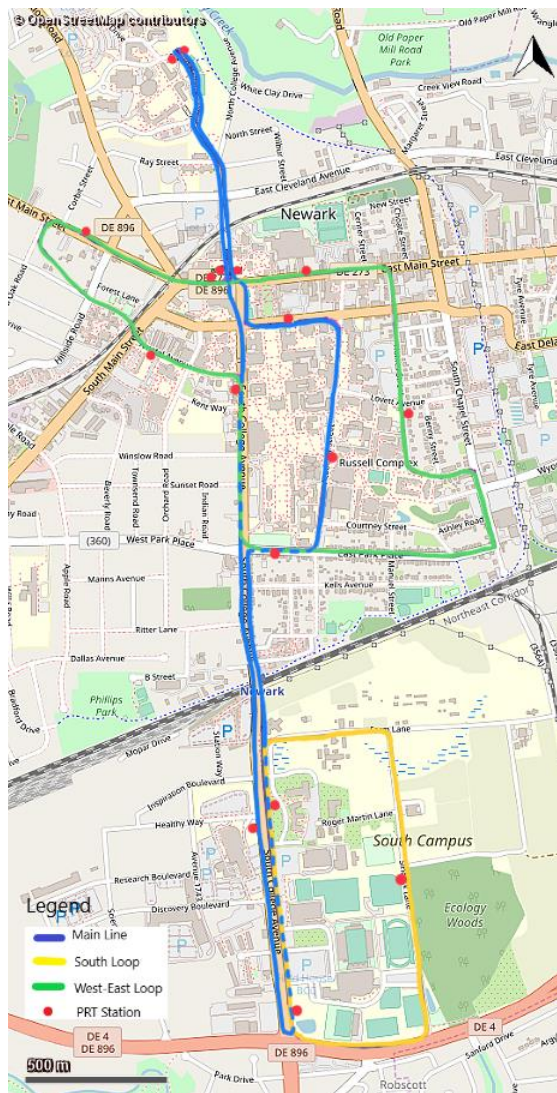


Figure 3-8 UD PRT Routes

Table 3-1 UD PRT System

	Main Line	West-East campus loop	South campus loop
Total Length(miles)	5.3	2.9	1.6
Guideway structure	Single track	Single track	Single track
Speed(mph)	40	40	30
Vehicle type	Supported	Supported	Supported
Vehicle volume (in person)	16	16	16
Average station distance (miles)	0.51	0.49	0.6
Average travel time between stations(min)	1.24	1.2	1.96
Stations	Laird Campus (2), Trabant Center (2), Main Campus, Morris Library, Wolf Hall, STAR Campus, South Campus	Trabant Center, ELI, Amy Music, Lauren Hall, ISE lab, Carpenter Sport Building	STAR Campus, South Campus, Bob Hannah Stadium

3.3.3.2 Station Design

The UD PRT system adopts a typical off-line station as shown in Figure 3-9 (Muller, 2009). Like bay stations in the bus system, the off-line station is on a bypass guideway and separate from the main guideway. The off-line station allows almost every vehicle to operate independently. Additionally, the bypass guideway provides extra distance for the vehicle when entering or leaving the station to accelerate or decelerate. Figure 3-10 is the UD PRT station in VISSIM simulation.

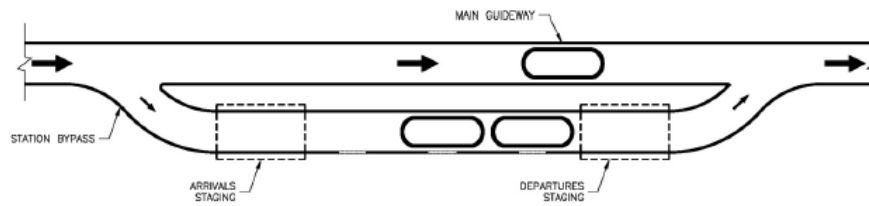


Figure 3-9 Off-line Station (Muller, 2009)

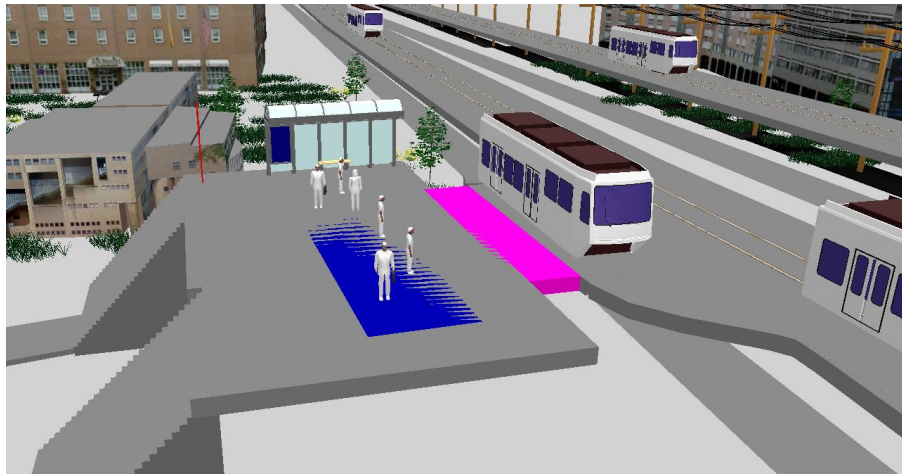


Figure 3-10 VISSIM Model of UD PRT Station

3.3.3.3 Cost Analysis

Multiple articles demonstrate that the total infrastructure cost, including guideway, station, and maintenance, makes up more than half of the capital cost.

Additionally, the guideway cost makes up a large part of the infrastructure cost. Figure 3-11 (J. E. Anderson, 2009) displays several PRT and other transit method guideway costs. The PRT guideway cost is shown having lower investment costs than others. The average PRT system guideway yields 9.6 million Euro per track-mile.

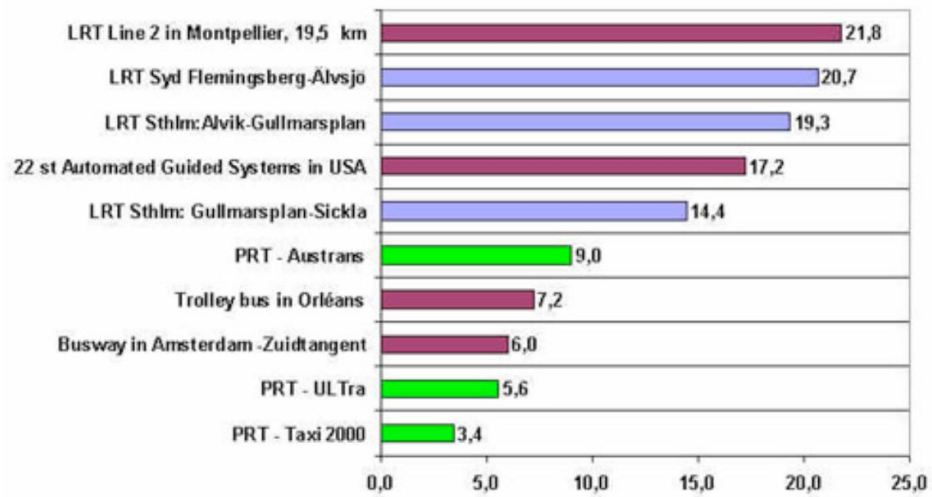


Figure 3-11 Investment Cost in MEuro per track-km (J. E. Anderson, 2009)

Based on the guideway cost of Ultra PRT system, the estimated cost provided by Dr. A. Kornhauser, Princeton University and other research about the average cost of PRT guideway (Tegnér, 2003) (Bly & Teychenne, 2005) (Kerr, James, & Craig, 2005), the following Table 3-2 describes the UD PRT guideways and operation cost.

Table 3-2 UD PRT system Cost

PRT Route Cost (million dollars)	Main Line	West-East campus Loop	South campus Loop
Guideway, Station, and Vehicle	44.8	28.1	14.8
Operating and Maintenance (per year)	0.4	0.2	0.1
Total	45.2	28.3	14.9

Chapter 4

SIMULATION AND DATA ANALYSIS

4.1 Network Objects Constitute

4.1.1 Base Data

Base data refers to the infrastructure in the network, including:

- Links with directions and specific lanes
- The connector between different links
- Length and location of public transport stop

4.1.2 Simulation Dynamics Data

Dynamics data used in a traffic simulation program, including:

- Traffic volume and vehicle compositions in each segment
- Priority rules of no signal control intersection
- Public transport lines and departure time

4.2 Network Simulation

4.2.1 Network Set Up

In order to build a more accurate model, realistic background selection is essential. For basic graphics parameters, OpenStreetMap (OSM) was chosen as the map provider. Based on OSM, links and connectors are used to describe the whole network. Each direction has a link with two lanes width of twelve feet.

The simulation road network should be considered mainly as Links. The connector should be used only when the link attributes change, such as the number of lanes, speed limit, and road channelization. The Connector has to avoid setting too long on the main road and overlapping with Links. When describing a vehicle steering at an intersection, it is generally not allowed to change lanes or overtake other vehicles. In this case, the steering path should use the Connector.

Figure 4-1 shows the UD PRT system in VISSIM simulation.



Figure 4-1 UD PRT VISSIM Network

4.2.2 Regulation

Traffic flows running on road facilities are often constrained by the physical conditions of road traffic facilities, by the travel constraints of adjacent vehicles, and by traffic regulations. Since traffic regulations vary depending on time and locations, various traffic regulations should be set and described before the simulation analysis.

Basic vehicle driving rules include speed control rules, priority rules, and signal control rules. UD PRT system only uses the first two rules.

1. Speed control rules

The vehicle travels at the desired speed on the road when there are no other vehicles and traffic rules. When the free-flow speed of the road network changes, as the traffic increases, the driving conditions of the road change, and it is often necessary to limit the speed of the vehicle within a particular section. After passing these restricted sections, the vehicle's speed is restored to normal. In VISSIM, there are two types of speed control: temporary vehicle speed changes, such as vehicle steering, use of deceleration zones, and permanent vehicle speed changes, using the desired speed decision point.

A deceleration zone is set in the section of the entry and exit each station and on some turning roads with small turning radius. When the deceleration zone is active, the vehicle automatically starts to decelerate as it approaches the deceleration zone.

2. Priority rules

VISSIM uses priority rules to specify the right of way to conflicting traffic. The priority rule includes a parking line (red line) and one or more conflict line (green line). According to the current road conditions at the conflict sign, the passing of the vehicle is controlled by the parking line. The road condition test at the conflict sign includes the minimum headway spacing and time interval.

Generally defined, the length of the conflict zone is the same as the minimum headway spacing. In the simulation, the current headway spacing depends on the distance between the first vehicle approaching the conflict sign and the conflict flag. When any part of the vehicle is above the conflict sign, the current headway distance is 0. If the current headway spacing is less than the minimum headway spacing, all vehicles that are close to the collision zone must park at the parking line.

The similar but more straightforward way to deal with conflict traffic is setting the conflict zone in VISSIM. The green area has the right of way in the conflict area; the vehicle on the red area has to wait for the vehicle in the green area. Figure 4-2 shows the conflict zone in the UD PRT system, the entry station and straight lane vehicle has the right of ways.

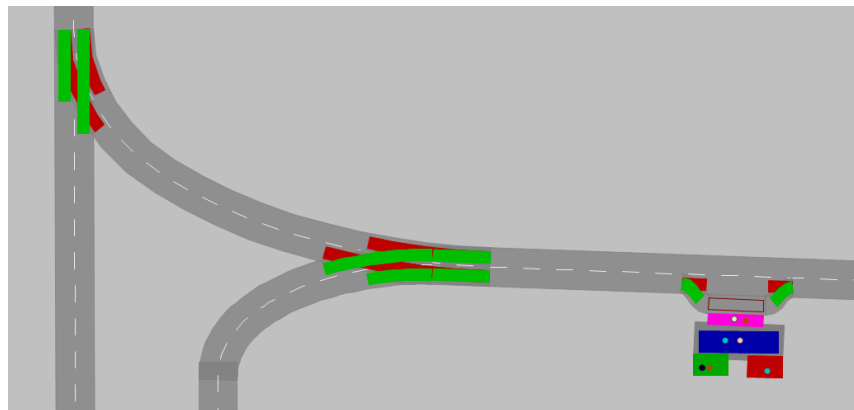


Figure 4-2 Conflict Zone

4.2.3 Baseline Parameters

Setting the model parameters is critical to ensuring the correctness and usability of the simulation results. The most basic simulation model parameters

include traffic flow, desired speed, and so on. In order for the simulation of the road network to be consistent with the actual, correctly reflecting the actual traffic flow path and driving rules, the adjustment of the simulation model parameters is also necessary to establish a good simulation model. The adjustment of the simulation model parameters can be performed separately or according to the overall effect.

1. Vehicle Data

Table 4-1 Vehicle Data

Vehicle type	Bus	
Speed distribution (mph)	40	Upper bound 46
		Lower bound 38
Color	Blue, Yellow, Red	
Occupancy (in person)	16	

2. PRT Base Data

The base data varies from station to station; the following tables are the detailed data of each station. Base Data of Trabant Center Station-M1 from Main Line is shown as an example in Table 4-2.

The Poisson distribution is suitable for describing the number of random events occurring in a unit of time (or space). If a passenger arriving at a bus stop appears randomly and independently at a fixed average instantaneous rate (or density),

then the number of occurrences of this event in unit time (area or volume) approximately obeys loose distribution. Thus, the Pedestrian input of each station is subject to Poisson distribution as shown in Figure 4-3.

As a comparison, three different departure times are used to run the simulation. By choosing the best performance result, the most proper timetable for the system can be determined.

The Trabant Center Station is the second station and first transfer station in Main Line; thus, the only passengers are from the first station, Laird Campus Station. The percentage of alighting passenger is calculated in Excel based on the OD matrix.

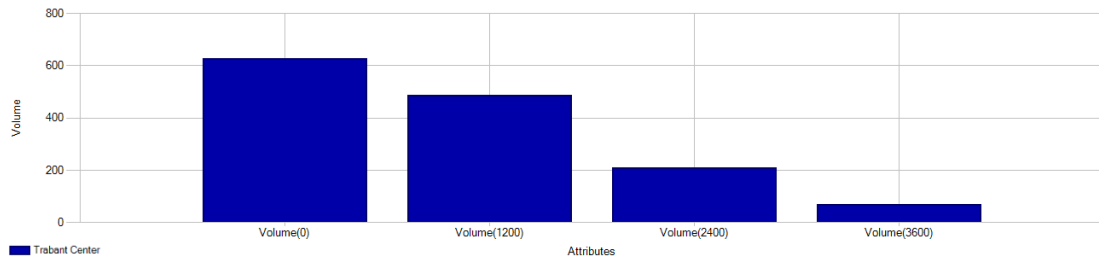


Figure 4-3 Pedestrian Input of Trabant Center Station

Table 4-2 Trabant Center Station Base Data

Time Interval	Pedestrian Inputs	Departure Time (s)	Dwell Time	Alighting Location	Alighting Composition	Alighting Percentage
0s	626	300; 600; 900	Minimum	1: Uniform	22: Laird Campus Station	23.70%
1200s	487					
2400s	209					
3600s	70					

4.2.4 Evaluation Configuration

Table 4-3 Evaluation Configuration

Evaluation Object		Evaluation Index
Link Segment		Density
		Delay
		Speed
		Volume
Node		Queue Length
		Vehicle Delay
		Person Delay
		Stops
Network	Vehicle	Delay Average/Total
		Travel Time Average/Total
		Speed Average
		Distance Total
	Pedestrian	Speed Average
		Travel Time Average
Stop Time Average		

4.3 Result and Performance assessment

4.3.1 Service and Evaluation Standers

With the advanced technologies applied in the field of PRT, the import of dynamic update standards could ensure the safety and efficiency of the system, and at the same time raise satisfaction regarding the level of service.

The following Table 4-4 is a partial evaluation standard applicable to the PRT system based on a bus system (Muller, 2009). Since this article does not involve monitoring management, it does not list the relevant standards. Chapter 4 has

thoroughly illustrated the route design. Therefore, the service design will be discussed in detail in this chapter.

Table 4-4 Evaluation Form

Category	Group	Standard item	UD PRT System (per line)	Qualified?
Route Design	Routh Level	Route Length	Max 20 min	Yes
		Stop Spacing	Max 0.6 mile	Yes
	Network Level	Route Coverage	Min 1.6 mile	Yes
		Route Overlapping	Only around Main Campus	Yes
		Route Structure	Max of 2 branches per route/loops around terminals	Yes
		Route Connectivity	Min of 1–2 transfer points	Yes
Service Design	Planning Level	Waiting Time	Min 0.3 min; Max 20 min per station	Need optimal
		Occupancy	Min 15%; Max 112%	Need optimal
		Headway	Min 2 min; Max 20 min	Yes
		Transfer	Max of 2 transfers for any O-D	Yes
		Passenger	Min of 28 per hour	Yes
	Monitoring Level	N/A		

4.3.2 Simulation Result Assessment

The quality of a PRT system's service can be affected by many factors. In this paper, the constant method of the control variable method is used to study various factors affecting the quality of PRT operation. The extra variables are other than the independent variable that could cause the dependent variable to change to remain constant to clarify the causal relationship in this experiment.

In general, the independent variable must be able to be manipulated, and the dependent variable must be able to be measured objectively. Thus, choose the vehicle headway and speed as independent variables, and select the passenger travel time as a qualitative measure to analyze the quality of a PRT system service.

As a comparison, VISSIM simulations include the different combination of two speeds and nine headways. Table 4-5 shows the different parameters.

Table 4-5 Simulation Parameters

Item		Abbreviation
Speed (km/h)	40	S1
	60	S2
Headway (s)	120	H1
	240	H2
	360	H3
	480	H4
	600	H5
	720	H6
	840	H7
	900	H8
	1200	H9

Each kind of simulation has been repeated several times to avoid extreme outline. The following Table 4-6 shows the passenger travel time in minutes through different headways and speed.

Table 4-6 Simulation Result (in minute)

Headway Speed	H1	H2	H3	H4	H5	H6	H7	H8	H9
S1	73.86	129.17	147.19	193.55	212.19	206.59	182.62	188.48	202.97
S2	61.31	130.54	153.55	169.70	177.82	184.38	162.04	173.93	182.42

Figure 4-4 demonstrates the pattern of the travel time of different routes; this travel time includes the passenger's waiting time and vehicle's operation time. As the length of the route increases, the impact of speed on travel time increases. The South Campus Loop is the least affected while the Main Line is affected the most. All three lines appear to have the same pattern. The travel time growing when the headway increased from 120s to 720s and slightly drops at 840s, then the travel time arises again.

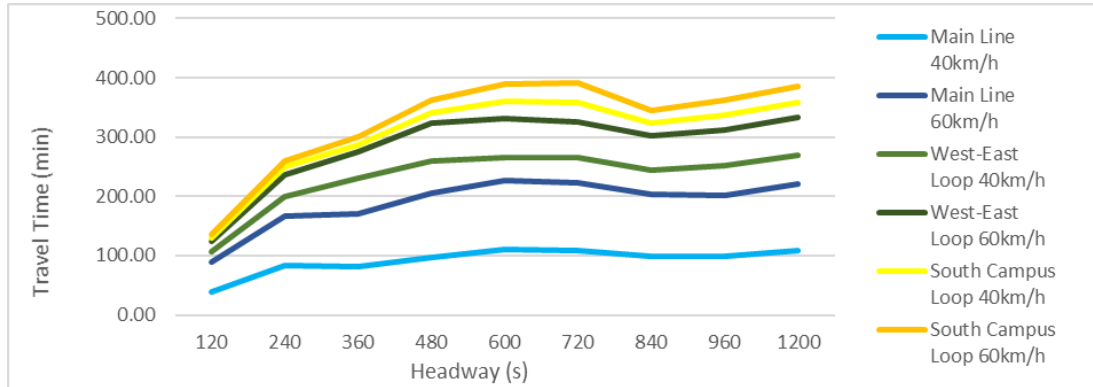


Figure 4-4 Route Travel Time

Figure 4-5 shows different waiting through stations. Except for Laird Campus starting station, the waiting time is diverse for each station. Basically, the waiting time of the station increases as the headway increases.

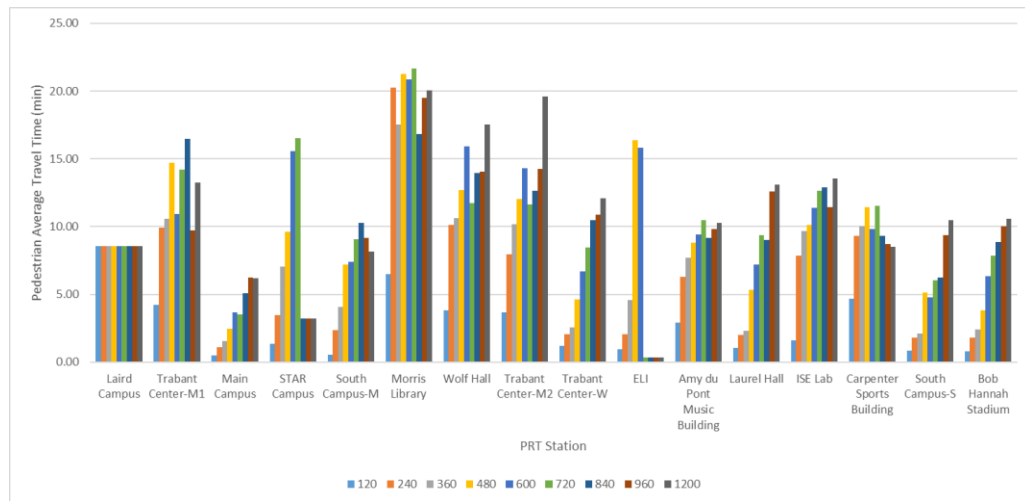


Figure 4-5 PRT Station Waiting Time

4.3.3 Data Analysis Based on MATLAB

Analysis of variance is a statistical method proposed by British statistician R.A. Fisher in the 1920s, which has a vast range of applications like production practice and scientific research. It is often necessary to study the effects of changes in production conditions or experimental conditions on the quality or yield of a product.

According to the number of analytical indicators (dependent variables), there are two kinds of analysis of variance: the one-way analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA)

Two-way analysis of variance is to analyze the contribution of variation from different sources to the total variation and to determine the influence of controllable factors on the research results. There are two types of two-way analysis of variance: one is a two-way analysis of variance without interaction, which assumes that the effects of factor A and factor B are independent of each other, and there is no correlation; the other is the two-factor interaction. Variance analysis, which assumes that the combination of factor A and factor B produces a new effect.

The sample needs to meet several basic assumptions of analysis of variance:

1. All samples are from a normal population;
2. These normal populations have the same variance

Therefore, the normality test and the homogeneity of variance test should be performed before the analysis of variance.

The first step is to call the Lillietest function to check if the sample obeys normal distribution. The null hypothesis is that the sample follows a normal distribution, and the alternative hypothesis is that it does not obey the normal distribution. Procedure and result are shown in Figure 4-6. The p-value is higher than

0.05 indicates that the null hypothesis is accepted at a significance level of 0.05, and the sample is considered to be normally distributed.

```
>> [x,y]=xlsread('C:\Users\10935\Desktop\Ch5.xlsx');
time=x(:,2);
speed=y(1:end,1);
speed_id=x(:,1);
for i=1:2
    timei=time(speed_id==i);
    [h,p]=lillietest(timei);
    result(i,:)=p
end

result =

    0.0584

result =

    0.0584
    0.0732
```

Figure 4-6 Normality Test

In the second step, the `Vartestn` function is called to check whether the sample obeys the normal distribution with the same variance. The original hypothesis is that the sample obeys the normal distribution with the same variance, and the alternative hypothesis is a normal distribution with different variances. Figure 4-7 shows the test result. The p-value of the test = $0.663 > 0.05$, indicating that the null hypothesis is accepted at a significance level of 0.05, and the sample is considered to be subject to the same normal distribution of variance, satisfying the underlying assumption of analysis of variance.

Group	Count	Mean	Std Dev
S1	9	170.736	45.6708
S2	9	155.077	38.9498
Pooled	18	162.906	42.4435
Bartlett's statistic	0.18999		
Degrees of freedom	1		
p-value	0.66292		

Figure 4-7 Homogeneity of Variance Test

After the normality test and the homogeneity test of variance, it is considered that the sample obeys the normal distribution with the same variance. The `anova2` function can be called from the MATLAB statistical toolbox for two-factor one-way analysis of variance. The format of the call is as follows: `=anova2(X, reps)`

The null assumption of the `anova2` function is:

- H0S: Each column of X has the same mean value (or the factor Speed has no significant effect on the experimental index)
- H0H: Each row of X has the same mean value (or the factor Headway has no significant effect on the experimental index)
- H0SH: The interaction between factors S and H is not significant

The null hypothesis should be rejected when the `anova2` function returns that the p-value of the test is less than or equal to the given significance level. The significance level of this experiment was 0.05.

The result is shown in Figure 4-8. The test p-value of factor H is less than the given significance level of 0.05, so it can be determined that the departure time has a significant influence on the running time. The factor S and the interaction of the two factors correspond to a test p-value higher than a given significance level of 0.05, so it

can be determined that the speed has no significant effect on the running time, and there is no interaction between them.

shows the distribution of the sample; most results clustered from 170 to 190. The optimal solution of the total travel time for all three lines, combining with the operation cost, will be S2H7. When speed at 60km/h and headway is 840s, the operation plan will be economical.

Analysis of Variance					
Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
S	4.4	1	4.44	0	0.9594
H	34054.1	8	4256.76	2.5	0.0217
S*H	45.3	8	5.67	0	1
Error	91837.2	54	1700.69		
Total	125941	71			

Figure 4-8 ANOVA Result

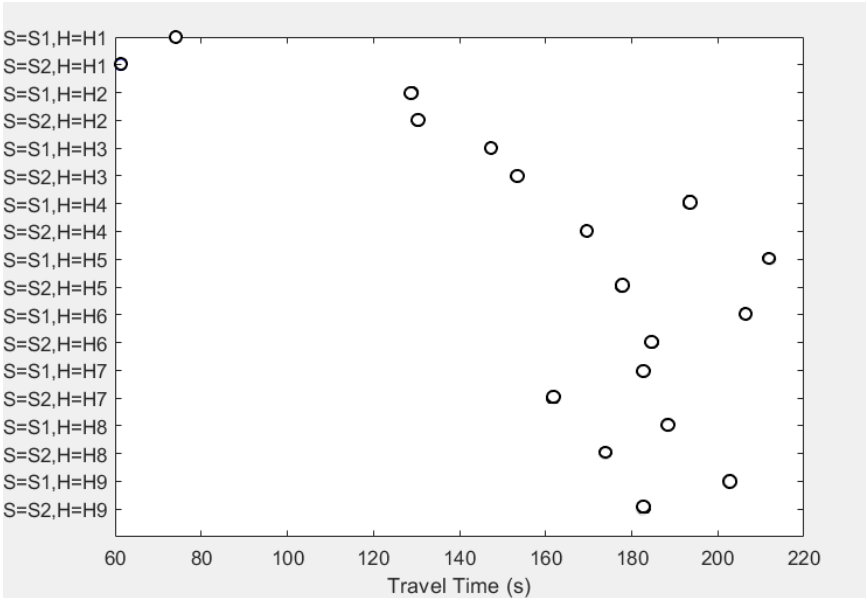


Figure 4-9 Result Distribution

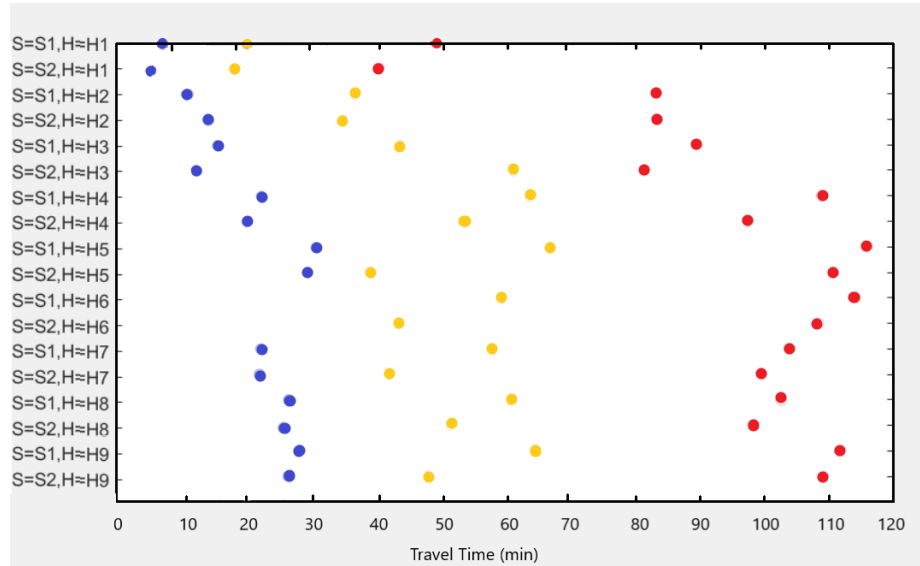


Figure 4-10 Route Travel Time

Figure 4-10 display the distribution of each line’s travel time. As can be seen from the figure, the optimal choice of the two loop lines remains the same. Considering the main line may be accountable for more massive passenger flow, it could reduce the headway and choose S2H3 instead. The final plan for UD PRT system is listed in Table 4-7.

Table 4-7 The UD PRT System Solution

	Speed(km/h)	Headway(s)	Vehicle	Travel Time (min)
Main Line	60	360	23	81
West-East Loop	60	840	16	42
South Campus Loop	60	840	8	8

Chapter 5

CONCLUSION AND FUTURE STUDY

5.1 Conclusion

This paper investigates the feasibility of applying the PRT system around the University of Delaware. The guideway network of the University of Delaware PRT system and the location of PRT station was described and enhanced. Basic PRT operation plan, the cost of construction and operation were initially estimated.

5.2 Future Study

Developing a new feasible PRT system requires a comprehensive and disciplined design process. Although this paper primarily focuses on network and operation scheme design, there are many other aspects is also essential. Following is some recommendations for the future study in this area.

There are many trips generated by faculty and staff of the University of Delaware around the campus area. In this paper, the UD PRT system network designed is only based on student trip distribution; this could result in an over or underrepresentation of travel demand. A more comprehensive traffic data set is acquired to build a more precise PRT system.

Another further area of study could be the construction plan of the PRT system. The plan of the construction according to the local geological and hydrological conditions and environmental test report such as the potential negative

impact of the PRT system on surrounding areas could be valuable in the design process of PRT system.

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Appendix

UNIVERSITY OF DELAWARE HOURLY TRIP DISTRIBUTION

Origin	Destination	Main Line Station				South Campus Loop				West-East Campus Loop Station							
		Laird Campus	Trabant Center	Main Campus	Star Campus	South Campus	Morris Library	Wolf Hall	Hannah Stadium	Bob Stadium	Star Campus	South Campus	Trabant Center	ELI Music	Amy Music	ISE Lab	Carpenter Sport Building
Main Line Station	Laird Campus	21	1281	1277	15	0	336	992	0	15	0	1281	0	1002	30	469	10
	Trabant Center	63	71	420	4	0	100	321	3	4	10	430	0	339	17	162	5
	Star Campus	3	104	114	6	0	33	36	10	6	24	71	2	66	22	32	5
	South Campus	0	593	623	4	0	161	461	0	4	0	593	0	502	12	196	7
South Campus Loop Station	Morris Library	0	432	444	4	0	27	319	0	4	0	432	0	351	10	126	2
	Wolf Hall	21	136	113	1	0	41	130	3	1	10	136	0	100	8	44	1
	Bob Hannah Stadium	0	165	161	2	0	32	81	0	2	0	165	0	134	10	59	2
	Star Campus	3	104	114	0	0	161	461	0	4	0	104	0	90	3	39	0
West-East Campus Loop Station	South Campus	0	593	623	4	0	100	321	3	4	10	593	0	502	12	196	7
	Trabant Center	21	430	420	4	0	100	321	3	4	0	21	0	339	17	162	5
	ELI	0	21	25	0	0	8	19	0	0	0	21	0	16	0	10	0
	Amy Music	57	646	588	11	0	155	442	10	11	20	646	2	40	40	236	11
Laurel Hall	ISE Lab	0	324	347	4	0	91	254	0	4	0	324	0	270	92	1	
	Carpenter Sport Building	21	430	420	4	0	100	321	3	4	10	430	0	339	17	5	
	Laurel Hall	0	166	161	0	0	42	111	0	0	0	166	0	128	5	52	