ABSTRACT

Title of thesis: A TRIP TIME COMPARISON OF AUTOMATED GUIDEWAY TRANSIT SYSTEMS

Reuben Morris Juster, Master of Science, 2013

Thesis directed by: Professor Paul M. Schonfeld
Department of Civil and Environmental Engineering

Automated People Movers (APM) and Personal Rapid Transit (PRT) are two of the main transportation modes in the realm of grade-separated automated transit technology. APMs can be seen in various US locations and resemble traditional heavy rail or light rail, as they all operate on fixed routes, but APMs are completely automated. PRT systems, which are not well established in the US, use low capacity vehicles to transport passengers directly from their origin to their destination, bypassing intermediate stations. Each type of automated guideway transit technology may have a niche where one type is preferable to the other. This study uses simulation to quantify the passenger levels and geographical contexts that are preferable for APM or PRT. The simulation results show that PRT tends to have lower trip times than APM if the PRT has shorter distances between stations, fewer passengers, and a more complex geometry.

A TRIP TIME COMPARISON OF AUTOMATED GUIDEWAY TRANSIT SYSTEMS

by

Reuben Morris Juster

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Advisory Committee:

Professor Paul M. Schonfeld, Chair
Associate Professor Mark A. Austin
Associate Professor Lei Zhang

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Chapter 1: Introduction

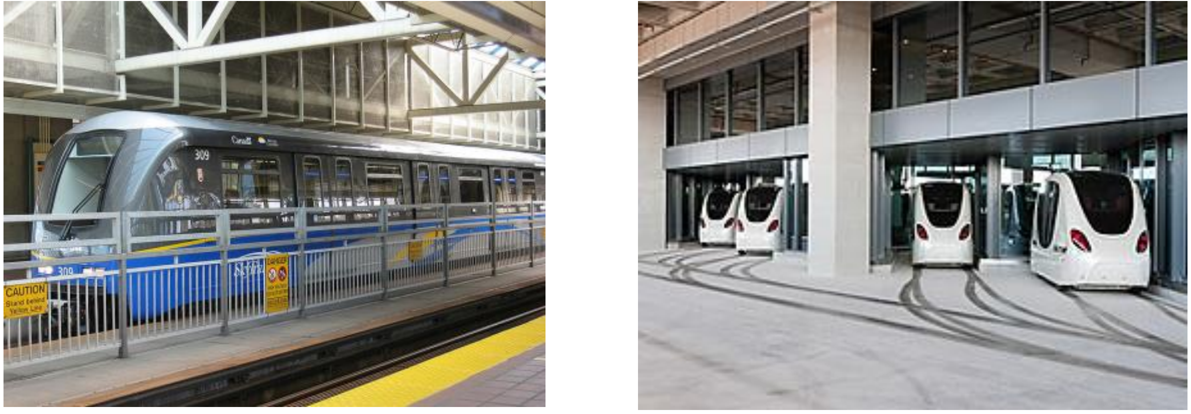
Automated fixed-guideway transit includes any type of transit that is completely driverless and whose motion is constrained by a guideway/ rail. There are two types of automated fixed-guideway transit that are currently being designed and constructed, namely automated people movers (APM), and personal rapid transit (PRT).

1.1 APM Background

The Airport Cooperative Research Program's (ACRP) Report 37, "Guidebook for Planning and Implementing Automated People Mover Systems at Airports", defines APMs as "systems [that] are fully automated and driverless transit systems that operate on fixed guideways in exclusive rights of way" (ACRP, 2010). Most people associate automated people movers with the traditional type of APM, which consist of train-like vehicles that move on rubber tires and powered via an electrified rail or propelled with a cable, but APMs include a family of different vehicles that are almost as diverse as automobiles (Lewalski, 1997). Figure 1.1.1 shows some APM examples. Monorail systems vary in shape and size, but all vehicles run above or are suspended below a single rail or beam (Moore & Little, 1997). Automated light rail and heavy rail resemble their non-automated counterparts, except that they are fully driverless. Those types of systems have a large capacity that can handle the travel demands of a busy activity center. Heavy rail transit systems feature fast trains with many high capacity cars that operate on a fully grade separate route. Light rail systems are similar, but vehicles tend to be shorter, can be articulated, and slower than heavy rail (Metro Cincinnati, 2010). The main difference between heavy and light rail systems are that the latter are designed to run on various types of right-of-ways, ranging from tracks in mixed traffic to completely exclusive ones. Many of the APM systems have platform screen doors as an extra security measure at unstaffed stations, thus increasing their resemblance to horizontal elevators.

Source: Planetizen, 2009
System: Miami Metro Mover
Type: Traditional APM

Source: Las Vegas Monorail, 2009
System: Las Vegas Monorail
Type: Monorail



Source: Wikipedia.org, 2009
System: Vancouver Skytrain
Type: Light rail

Source: Time Magazine, 2011
System: Masdar City PRT
Type: PRT

Figure 1.1.1: Automated People Mover Types

The first known automated people mover was allegedly built in the 16th century in Salzburg, Austria. It used a system of water tanks, ropes, and gravity to move vehicles that carried goods up a 625 feet hill with a 67% slope. The system is still in use today, but with several modern upgrades. No APM was built for hundreds of years until the 20th century. During the 1950s, experimental people movers were built, but only survived for a few years. The South Park Demonstration Project, built by the Westinghouse Electric Corporation, was an ill-fated attempt to start an automated people mover system in Pittsburgh and only survived from 1965 to 1966.

Westinghouse’s efforts were not all in vain. In the 1970s, construction of APMs proliferated, especially in the U.S., using Westinghouse based technology. The Tampa International Airport’s automated people mover was the first people mover ever built at an airport. Completed in 1971, this people mover was vital in the airport’s innovative design connecting several satellite airside concourses to a central terminal. The airport was able to expand its footprint and capacity without dramatically increasing the walking distance of passengers (ACRP, 2010). Continuing today, APMs have allowed airports to grow and accommodate super-hub size traffic without requiring passengers to walk unreasonably long distances.

APMs in non-airport activity centers have been less popular in the United States than airport APMs. Activity center people movers finally began operations in the 1980’s, with the exception of the experimental Morgantown PRT (considered to be Group Rapid Transit, GRT), which started operation in 1975. The Urban Mass Transportation Administration (UMTA, the predecessor of the Federal Transit Administration) with direction from Congress started the Downtown People Mover (DPM) Program through which cities across America could submit proposals for DPMs. Accepted proposals would receive generous federal government funding. Downtown people movers act as circulators in the major workplaces and activity centers of central business districts. Four cities were selected out of thirty eight submitted proposals, none of which were constructed. A second selection process yielded three other cities which were eventually selected for DPMs including Miami, Jacksonville, and Detroit (Sproule, 2004).

No other downtown people movers have been built in the U.S. since, but many other non-airport APMs have been built. Las Vegas has multiple people movers that connect several different hotels, casinos, and other attractions. Large medical campuses such as the Indiana University Health Complex or Huntsville Hospital System each have an APM to reach multiple hospitals. The Las Colinas Personal Transit System (APM) circulates people around a planned suburban community. In other countries, APMs have taken on the role of rapid transit, resembling light rail or high capacity heavy rail. Skytrain provides Vancouver, Canada with metro capacity and speed without any train operators since the 1980s.

1.2 PRT Background

PRT is another type of automated fixed-guideway transit that utilizes smaller vehicles than traditional APMs, but provides passengers with direct transportation from origin to destination. PRT is a type of APM, but in this thesis, APM refers to the traditional type of automated people movers. PRT enables direct transportation with off-line stations that contain a set of tracks for vehicles to decelerate and dwell at stations, and another set of tracks to bypass stations at full speed. PRT networks can be built with complex geometries that cover an entire town without needing multiple routes as an APM would need. The few PRT systems that exist use multiple four person unpaired vehicles that are battery powered, but vehicles can fit six people or be powered by an electrified rail (The Times of India, 2011; Taxi 2000).

PRT is a relatively new mode of transportation that combines features of APMs and taxis. PRT combine the grade separation and automation of APMs with the capacity and direct origin to destination transportation capability of taxis. PRT vehicles are not impeded by other PRT vehicles stopped ahead at stations since PRT stations have their own off-line tracks. Since PRT vehicles travel directly from origin to destination and stations are separated from the main travel guideway, PRT is not restricted to simple linear networks (Vectus, 2009). The greatest potential for PRT is with dense networks that cover an entire town as shown in Figure 1.2.1.

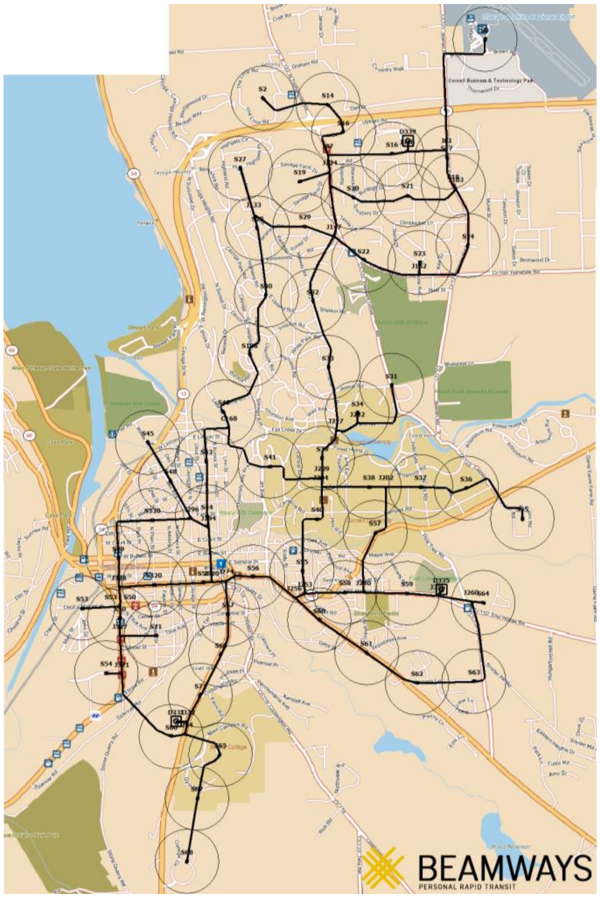


Figure 1.2.1: Ithaca PRT Network
Source: Beamways (2008)

The theoretical Ithaca, New York PRT system created by Beamways would consist of about 24 miles of track with 59 stations and 750 vehicles. This system could support the potential 5000 rush hour trips of the area's 50,000 residents and students. The average wait time for a vehicle would only be 5 seconds (Beamways, 2008). The Ithaca system is only one of the many potential PRT systems that could fulfill most of the transportation needs of a large community.

PRT features small vehicles that require smaller and less expensive stations and structural components than APM. These small vehicles may appear to minimize the potential capacity of the system, but smaller vehicles allow smaller headways. Headways as small as 0.5 seconds are possible, giving PRT the potential capacity of 28,800 passengers per hour per direction with four persons per vehicle, but PRT currently operates with 3 second headways limiting the capacity to

4,800 passengers per hour per direction. PRT’s main disadvantage is its vehicle performance, which is slower than APM, reaching speeds only up to 30 mph and acceleration of around 8.2 ft/sec^2 (Vectus, 2009).

The notion of PRT was first conceived around 1953 by Donn Fichter, who wrote specifically of a PRT like system in his 1964 work titled, “Individualized Automated Transit and the City”. He thought there should be a transportation mode that could be integrated with urban landscapes with inexpensive and small guideways as well as have service that could meet the transportation needs of individual riders. Much of the PRT research was performed independently until the Urban Mass Transportation Act was enacted in 1964. After Congress approved the act, multiple federal actions supported the progress of advanced transportation systems including PRT. This led to the development of the first PRT-like system, the Morgantown PRT in the 1970’s. The USA was not the only country to research PRT technology, the central governments of many Western European countries and Japan funded PRT test systems in the late 1960’s and 1970’s. None of the past PRT research projects led to a marketable product except for the German Cabintaxi system.

The PRT research in the 1980’s was concentrated on the Advanced Group Rapid Transit program that led to recommendations, but did not produce any functioning PRT or PRT-like system. PRT research restarted in 1990 when the Chicago Regional Transportation Authority (RTA) teamed up with the Raytheon Corporation to build a PRT system in the Chicago area. Phase one of the project involved selecting which company’s technology would be used for the study. RTA selected Taxi 2000 based technology. For phase two, a 2,200 foot pilot system was built with an off-line station and three vehicles. This system ran successfully, and proved that the technology could handle 2.5 second headways. The third and unfortunately last phase of the project involved building a demonstration PRT that would actually be used by passengers. The third phase along with the rest of the program was canceled in 2000 due to concerns of inflated costs and poor ridership projections (Carnegie & Hoffman, 2007).

1.3 Problem Statement

Airports build rail transit to expanded their facilities and increase connectivity between their existing facilities. Transit agencies build rail transit as part of their mission to provide quick and convenient transportation services. Airport rail transit almost exclusively uses automated fixed-guideway technology while transit agencies usually have onboard train operators (non-automated). Many transit agencies around the world are beginning to embrace the automation of their rail lines, which result in creating APM. Vancouver, British Columbia's light rail system uses APM light rail technology, and Paris has already built one automated heavy rail line whose success sparked interest into automating existing lines (Translink, 2012; Jampala, 2011).

Before 2000s, the only type of automated fixed-guideway transit that any entity would consider was APMs. Since then, the Masdar City and London Heathrow's PRT became operational in November 2010 and September 2011, respectively, proving the PRT technology is ready for the twenty first century. (2getthere, 2012; Ultra Global PRT, 2012). With the two different types of automated fixed-guideway transit, which type of automated guideway transit is preferable for a certain project? APMs can move substantial crowds at high speeds, but PRTs offer point to point service. This thesis will quantitatively define where each type of system is preferable through simulation trials since there are not enough comparable real life systems to contrast.

1.4 Objective

The objective of the thesis is to enable agencies to choose the right type of automated guideway transit based on passenger travel and waiting time. Other factors such as construction costs, operating costs, and environmental impacts are very important factors when deciding which mode to implement for a transit system, but are difficult to quantify for PRT since there are only two systems currently operating. The lack of other measures of effectiveness is covered in Chapter 3. Agencies would be able to input the specifications (geometry and passenger demand) of their proposed automated guideway transit system to discover which type of system has lower trip times. Results from this study may also be used to improve the design of future transit projects.

1.4 Organization

The contents of the rest of this thesis are divided into seven chapters. Chapter 2 provides the literature review that covers APM/PRT's modeling, capacity analysis, and a comparison of the modes. Chapter 3 summarizes the simulation tools used to evaluate APM and PRT. Chapter 4 describes how the simulation scenarios were chosen and constructed. Chapter 5 summarizes the simulation results. Chapter 6 provides an example on how the scenario summaries may be used to choose between APM and PRT. Chapter 7 provides a sensitivity analysis that gages how assumptions made in each mode's acceleration and velocity values affect the simulation results. Chapter 7 also covers the different capacities of each mode. Lastly, Chapter 8 concludes this thesis and elaborates on some additional areas of research.

Chapter 2: Literature Review

The topic of comparing traditional APMs and PRT is not well researched with only a few papers available, but there is bountiful literature on APMs and PRT individually. The literature review for this thesis is divided into three sections: Automated People Movers, Personal Rapid Transit, and PRT and APM Comparisons.

2.1 Automated People Movers

Most traditional APMs are built as short haul transit in airports or specialized activity centers such as central business districts or campuses. One of the scenarios modeled in this thesis includes a long line-haul type system which resembles a typical heavy rail corridor. This type of system is often implemented as a substitute for a light rail or heavy rail line, transporting commuters across cities. Shen, Zhao, and Huang (1995) proved that line-haul type APMs are effective at transporting passengers by reviewing existing line-haul APMs including the Vancouver Skytrain in Canada, Lille Metro in France, and the Wenshan Line of the Taipei Metro in Taiwan. The systems ranged in length from 7.2 to 17.9 miles with 12 to 36 stations at the time the paper's publication. All systems have since been extended. Shen et al. showed how each line-haul APM system had the capacity and the operating specifications to compete with other forms of line-haul transit. The systems operated at relatively high capacities with headways as low as 1 minute and their fleets consisted of trains with a capacity of up to 600 passengers per train. The maximum capacity along a point was 25,000 passengers per hour per direction. The trains could reach speeds of up to 56 mph (Shen, Zhao, & Huang, 1995). The capacity was on par with light rail, but on the low end for heavy rail. The speed was comparable to light rail and a bit slower than heavy rail (Carnegie & Hoffman, 2007). The capital cost figures for each of the APM systems were highly variable and depended on how much of the alignment was at-grade, elevated, or underground. For example, the primarily elevated Skytrain cost about $98.6 million per mile, while the mostly underground Lille Metro cost about $164.6 million per mile. In comparison, the average cost per mile for light rail and heavy rail at the time of the study and adjusted to 2012 dollars was $105.8 and $240.7 million per mile, respectively. In the US and other developed countries, employee costs make up the largest portion of costs, which APMs minimize through the lack of on-board operators. Each Vancouver Skytrain employee supported about 630,000 passenger miles compared to 221,000 passenger miles for heavy rail and 76,300 passenger miles for light rail. As line-haul transit systems, APMs have the performance, capacity, and cost to be considered along with non-automated heavy rail and light rail (Shen, Zhao, & Huang, 1995).

Lin and Trani (2000) developed a sophisticated APM simulation model using the specialized simulation software EXTENDS. Their simulator, APMSIM, was capable of modeling passenger/vehicle movement, system performance, and energy consumption based on a number of input blocks. Besides the simulation specifics and station component blocks, there were a number of guideway blocks that included two-way switches, merge diverge, single-lane loop, pinched loop, turnaround, and single lane blocks. The simulation user would assemble the blocks together to create an APM model. The user specified through blocks the passengers' origin destination pattern, network geometry, and demand over time. The simulation assumed:

- Passengers first exit vehicles before new passengers enter
- Boarding time per passenger was deterministic (though it was possible to use a distribution)
- Acceleration was based on equations of motion
- The braking rate was constant

Lin and Trani used APMSIM to model Atlanta Hartsfield International Airport's Plane Train. For that particular example they assumed that:

- Each vehicle had two doors that took 1.5 seconds to open/close and took 1 sec for a passenger to enter/exit each door
- Braking rate was 1 m/sec^2
- Station dwell time was 35 seconds
- Headway between trains must be a minimum of 120 seconds apart

The simulation successfully allowed them to model energy consumption, waiting time, queues at stations, and many other variables of interest (Lin & Trani, 2000).

ACRP 37, "Guidebook for Planning and Implementing Automated People Mover Systems at Airports", provided a variety of information on APMs. One of the most important issues was what instances should an APM be considered at all. If a trip is short enough, the station access time could make walking or moving walkways quicker than automated guideway transit. Figure 2.2.1 shows for which distances each type of intra-airport mode is preferable.

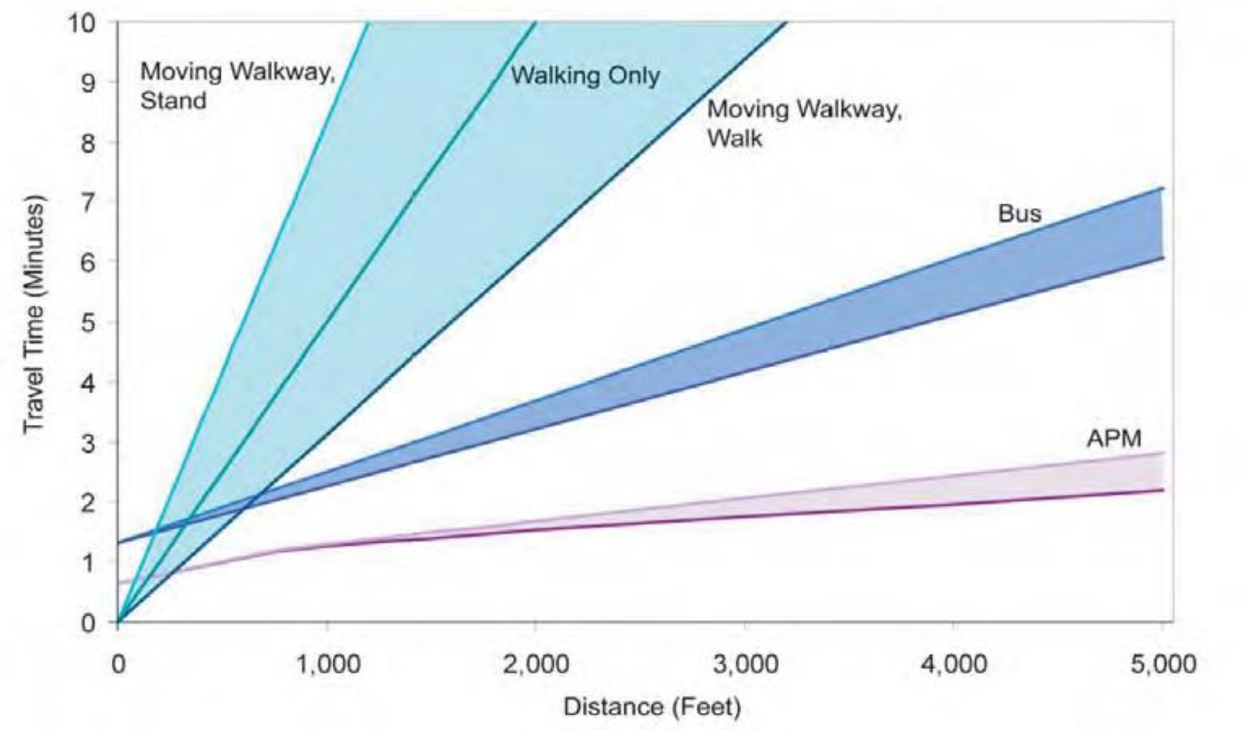


Figure 2.1.1: Intra-Airport Mode Comparisons
Source: ACRP (2010)

For trips under 300 feet, walking or moving walkways was the fastest. The travel time savings for APMs really started to pay off after about 800 feet when the dwell time and stopping sequences had less of an effect on the overall trip time.

ACRP 37 also had recommendations on the design and operation of the system. When designing an APM’s alignment, ACRP 37 recommended curve radii greater than 300 feet (91.5 meter) and a bare minimum radius of 150 feet (45.72 meter) which drastically impacted allowable speed. Minimum allowable headway between trains was recommended as 1.5 minutes. Maximum speeds varied for each vehicle type, but were typically 32 to 40 mph (ACRP, 2010).

2.2 Personal Rapid Transit

Gluck and Anspach (1997) used PRT2000 NETSIM, a PRT simulator, to run various sensitivity analyzes on PRTs. In the first analysis, average trip length and trip speed was shifted in a system with 100 vehicles to yield how many vehicle trips per hour the PRT can produce.

The simulations showed that the higher the average trip speed and lower the average trip length, the more trips per hour the system was able to supply. Increasing trip speed from 20 to 30 mph increased the capacity of the system by about 50%. Doubling the average trip length halved the capacity. During certain periods of time, especially rush hours, trips tend to go mainly in one direction and with PRTs, empty vehicles must run against the direction of travel to make up for the "unbalanced" demand. Gluckand Anspach showed that the capacity of a system decreased as its demand became more directionally unbalanced. For example, the transit route in Figure 2.2.1 was 100% directionally balanced between 0 and 0.5, and 0% balanced between 0.5 and 1. Even though the sum of passengers in both directions stayed constant throughout the route, the region between 0.5 and 1 was on the verge of being overloaded since all the passengers rode the route in one direction. Lastly, with lower travel speeds, the system could accommodate more vehicles, though not necessarily more trips (Gluck & Anspach, 1997).

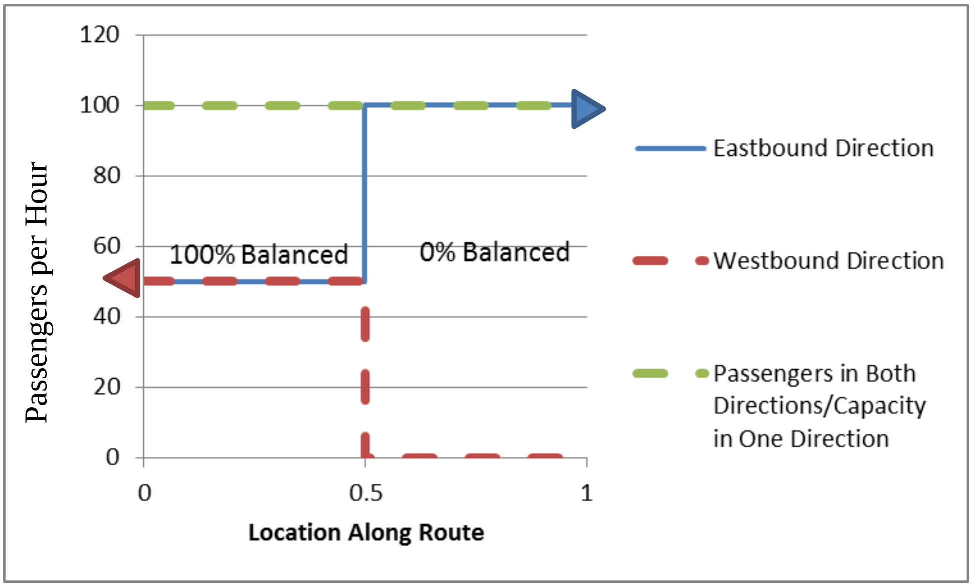


Figure 2.2.1: Directional Imbalance Example

Gluck and Anspach (1997) looked at how different travel characteristics could affect the capacity of the PRT system, but what about the capacity of the PRT stations themselves? Schweizer, Mantecchini, and Greenwood (2011) specially studied the capacity of the PRT stations. The capacity of the two main types of PRT stations, serial off-line (figure 2.2.2) and sawtooth (figure 2.2.3) stations was examined. Serial type stations typically have a single platform where vehicles queue up to accept passengers. The first vehicle to enter is the first vehicle exit the station. The serial type station had the best capacity, theoretically able to handle almost 800 vehicles per hour assuming the stations had 12 berths and each vehicle was loaded with four passengers with heavy luggage. 12 berth stations had the capacity for over 1000 vehicles per hour if there was only one passenger without baggage per vehicle. The major flaw for this station type was that loading a slow passenger will slow down the entire station (Schweizer, Mantecchini, & Greenwood, 2011).

Sawtooth type stations, which resemble angle parking spaces, allow for vehicles to independently maneuver in and out of berths. Passengers loading or unloading in one vehicle does not interfere with other vehicles since the berths are out of the way of the main station track. The drawback of this station type is the capacity, which the study estimated to be only about 450 vehicles per hour for a 12 berth station with any type of passenger(s). Although loading time was irrelevant, the time it takes for a vehicle to find an empty berth, maneuver in, and back out of a berth decreased the capacity below the serial type station. A high capacity sawtooth with overlapping curved platforms was proposed, but its capacity was still less than the serial type stations with passengers that take long to load and unload (Schweizer, Mantecchini, & Greenwood, 2011).

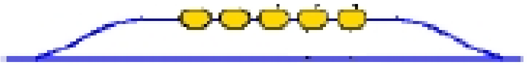


Figure 2.2.2: Five Berth Serial Type Station
Source: Schweizer et al. (2011).

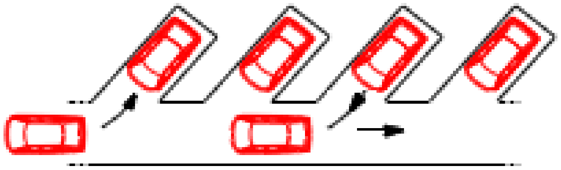


Figure 2.2.3: Four Berth Sawtooth Station w/ Vehicle Entering (Left) and Exiting (Right) Berths
Source: Schweizer et al. (2011).

Juster and Schonfeld (2013) performed a series of sensitivity analyzes on a linear PRT system with evenly spaced stations and unequal trip distribution. The base vehicle characteristics for the simulation were:

- Max Velocity- 15 meters / second
- Minimum Allowable Headway- 3 seconds
- 4 seats / vehicle
- 1100 vehicles

Each of the sensitivity analyzes adjusted one variable while keeping the others constant.

Figure 2.2.4 shows how each of the variables affect average travel time (the time spent moving in the vehicle).

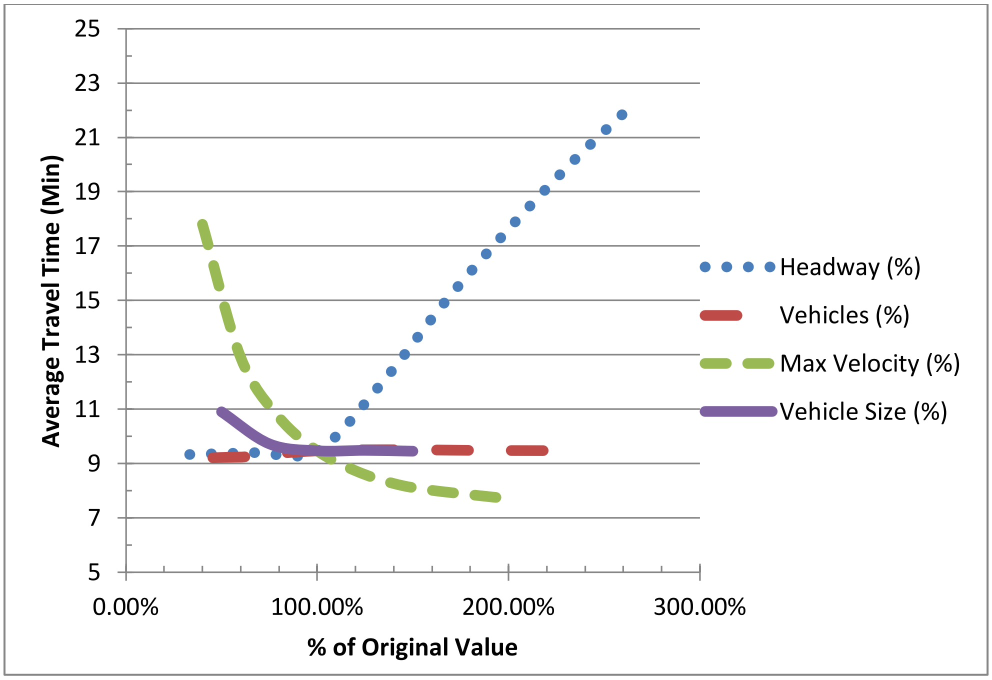


Figure 2.2.4: Average Travel Time Sensitivity to Model Variables
Source: Juster & Schonfeld, (2013)

When the authors decreased the minimum allowable headway, it had little effect on travel time, but increasing it greatly increased the travel time. The greater the vehicle velocity, the lower the system's average travel time. Smaller vehicle size slightly increased the travel time and adjusting the number of vehicles had no effect. Figure 2.2.5 displays the variables' effect on average wait time.

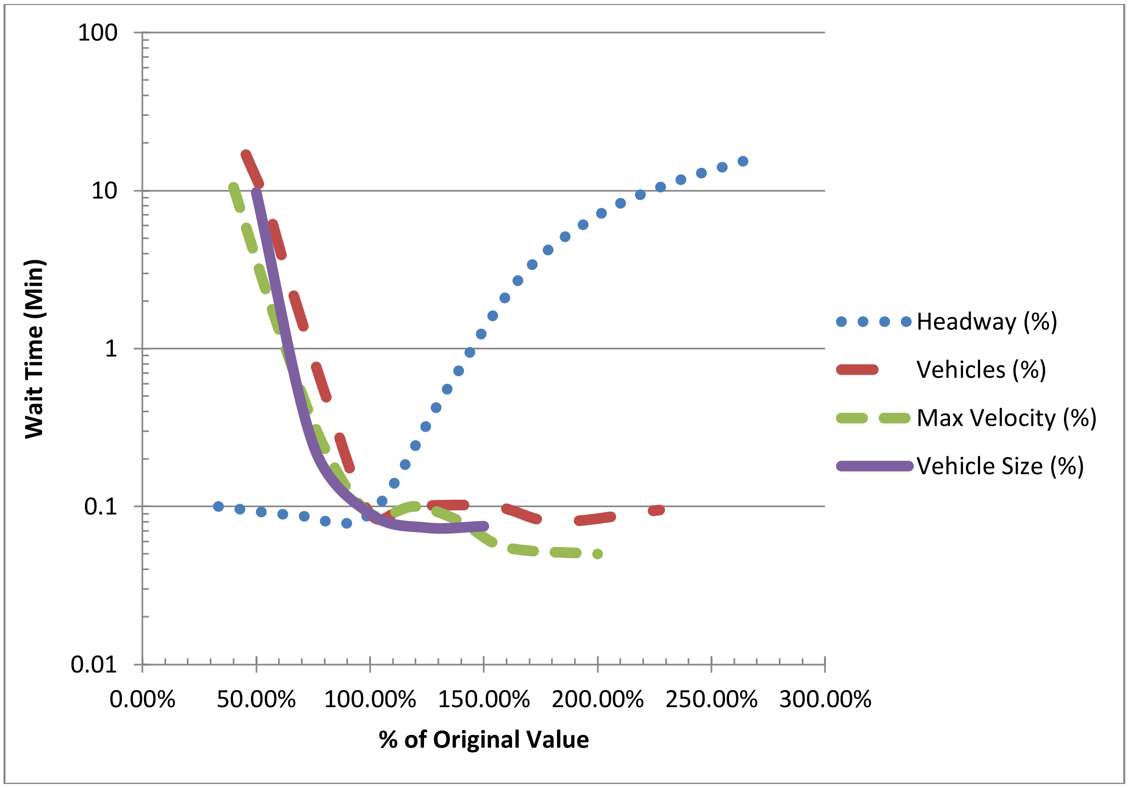


Figure 2.2.5: Model Variables' Effect on Wait Time
Source: Juster and Schonfeld, (2013)

When the number of vehicles, maximum velocity, and vehicle size decreased, the wait time increased. When those variables were increased, the wait time decreased, but in an unstable manner. The phenomenon was most likely due to the small wait time values. When the variables were set to their original levels, the wait time was below 6 seconds. Any slight change to the low wait time would seem dramatic on the graph. Increasing the minimum allowable headway increased the average wait time. The results of Juster and Schonfeld (2013) showed how certain system characteristics effect the operation of a linear network, but the results might not hold for a different system with a different configuration.

2.3 PRT and APM Comparison

Lowson (2003) was the most similar study to this thesis. He compared how station spacing affects the average travel time and speed for PRT, buses, and APM. The study incorporated walk (access), wait, and travel time on a linear corridor for each mode. Buses' trip time was inferior to the other two modes. Figure 2.3.1 shows the trip time compared to average stop separation for APMs and PRT.

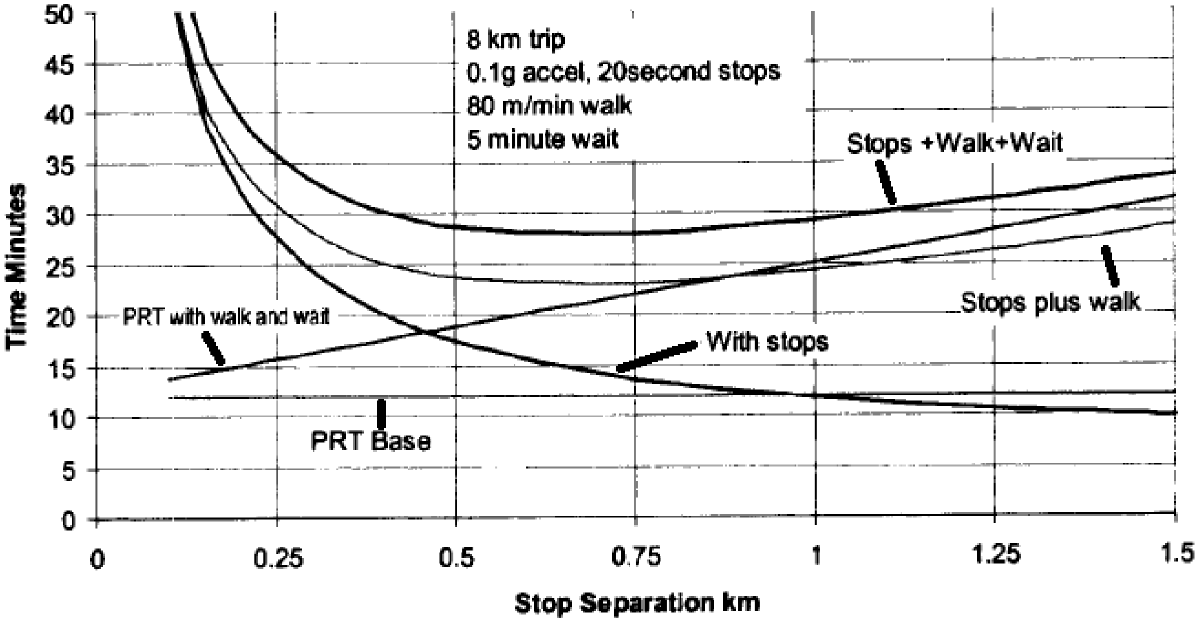


Figure 2.3.1: LRT/APM Compared to PRT
Source: Lowson (2003)

As one would expect, PRT was superior when the stop separation is small, but as the distance between stations increased, PRT's time advantage dissipated. When considering that Lowson assumed the APM and PRT's average wait time to be 5 minutes (10 minute headway) and 30 seconds respectively, APM was the superior mode with stop separation greater than 1.25 km (Lowson, 2003). There were many assumptions in Lowson's study that reduce the realism of the results. The system was simplified to an infinite linear corridor, which only fits a few real-life systems. Many PRT and APM systems have complex curves and branches to cover a wider area. Network capacity's effect on travel times was also ignored in the case that too many passengers can increase the travel time (Lowson, 2003).

Juster and Schonfeld (2013) compared a light rail (LRT), bus rapid transit (BRT), and PRT alternative for the real life application of the Maryland Transit Administration's (MTA) Purple Line Project. The Purple Line was a linear transit line with stations approximately the same distance from each other, but with an uneven trip distribution. Some multimodal stations (i.e. Purple Line stations with Metrorail, commuter rail, Amtrak, and bus connections) had over 12 times the trip origins and destinations as adjacent unimodal stations. Although the LRT and BRT alternatives were not APMs, they were transit modes that stop at each station, like traditional APMs. The paper superimposed a PRT network system on top of the Purple Line’s planned alignment using the BeamEd PRT simulator, the same program utilized for PRT modeling in this thesis. The trip time and cost comparison is shown below in Tables 2.3.1 and 2.3.2.

Table 2.3.1: Purple Line Trip Time Comparison

Mode	Average Peak Hour Travel Time (Minutes)	Average Peak Hour Wait Time (Minutes)
LRT	11.2	3.0
BRT	13.6	3.0
PRT	9.06	0.12

Source: Juster & Schonfeld, 2013

Table 2.3.2: Purple Line Cost Comparison

Mode	Original Estimate Cost ($million)
LRT	1600
BRT	1200
PRT	319

Source: Juster & Schonfeld, 2013

Based on the tables above, PRT was both a faster and cheaper mode of transportation and should be evaluated for urban transit projects. They wrote that future research should be conducted on what instances PRT should be implemented over other modes since they only examined a single linear system with equal station spacing and an uneven trip distribution (Juster & Schonfeld, 2013).

Chapter 3: Methodology

Multiple simulation trials were created for this thesis since there are not enough real life examples to aggregate and compare. PRT and APM were modeled with their own software which each has its separate input format, output format, assumptions, and limitations. Even though each mode used different software, the input for each scenario was identical. The settings for both PRT and APM are programed to resemble systems with the highest possible capacity, since the goal of this thesis is to find which type of automated guideway transit can handle which type of loads for specific geometry, rather than optimizing the number of vehicles. Trip time is the measure of effectiveness (MOE) in this thesis, though other MOEs such as cost were also considered.

3.1 APM Simulation Methodology

The APM model, Automated People Mover Simulation Model (APMSM), is a Java based simulation that runs directly from code without a graphical user interface (GUI). APMSM was created by the author to estimate APM system performance and energy consumption. APMSM requires the user to input the system geometry, service routes, train characteristics, and passenger demand. Once the simulation is running, a set of rules govern vehicle motion and passenger distribution. The actual operation of an APM is complex, and APMSM makes many assumptions to best approximate the actual operation without being computationally intensive. Some of the assumptions include deterministic passenger arrival, two-dimensional operation, and perfect performance. After the simulation finished, the user has multiple output files available to show the system performance down to each train and second.

3.1.1 APMSM Input Requirements

APMSM required a large amount of input to run each simulation. See Figure 3.1.1 for the APMSM hierarchy.

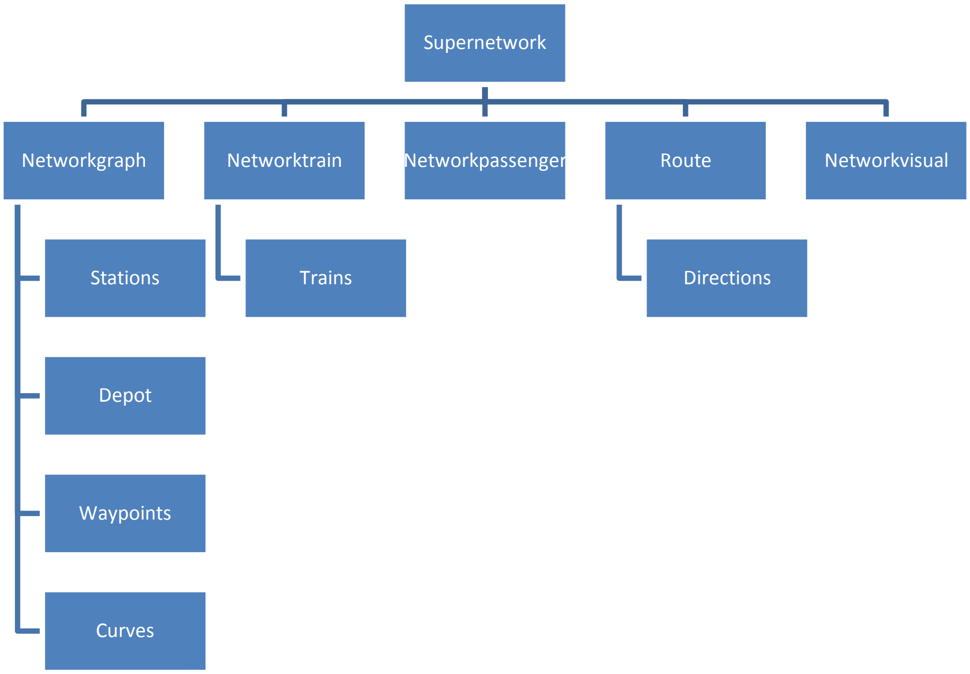


Figure 3.1.1 APMSM Hierarchy

Each scenario for the thesis needed its own Supernetwork, which contained all the components needed to create a unique APM. By default, each Supernetwork contained a:

- Networkgraph- Contained all the APM track and station components
- Routes- Contained different groups of stations and directions
- Networktrain- Contained all the trains and the rules that dictate the trains' movement
- Networkpassenger- Contained the passengers and demand levels
- Networkvisual- Helped the user visualize the Networkgraph

Each scenario's Networkgraph started with the creation of stations. Stations consisted of a name, x coordinate, and y coordinate. The x and y coordinates could be in any unit, but needed to be consistent with the other units used in the simulation. For this thesis, they were in meters. The stations were then connected with track sections including one-way and bidirectional tracks. The simulation assumed the track sections were straight unless waypoints or curves were created in the Networkgraph. Waypoints acted as intermediate points between stations. Curves are a series of waypoints and connections based on the user's specified radius and number of intermediate points. Curves and waypoints were essential for creating the complex geometries in this thesis. Every scenario's Supernetwork required a depot to store the trains and acted as the trains' starting location during the simulation. A depot was usually placed at one of the ends of a network. Creating the Networkgraphs was a tedious process and coding mistakes were possible. To verify that everything was input correctly, a Networkvisual was created to get a picture of the Networkgraph. A comparison of a sample Networkvisual and the official map of the sample system are shown below in Figures 3.1.2 and 3.1.3.

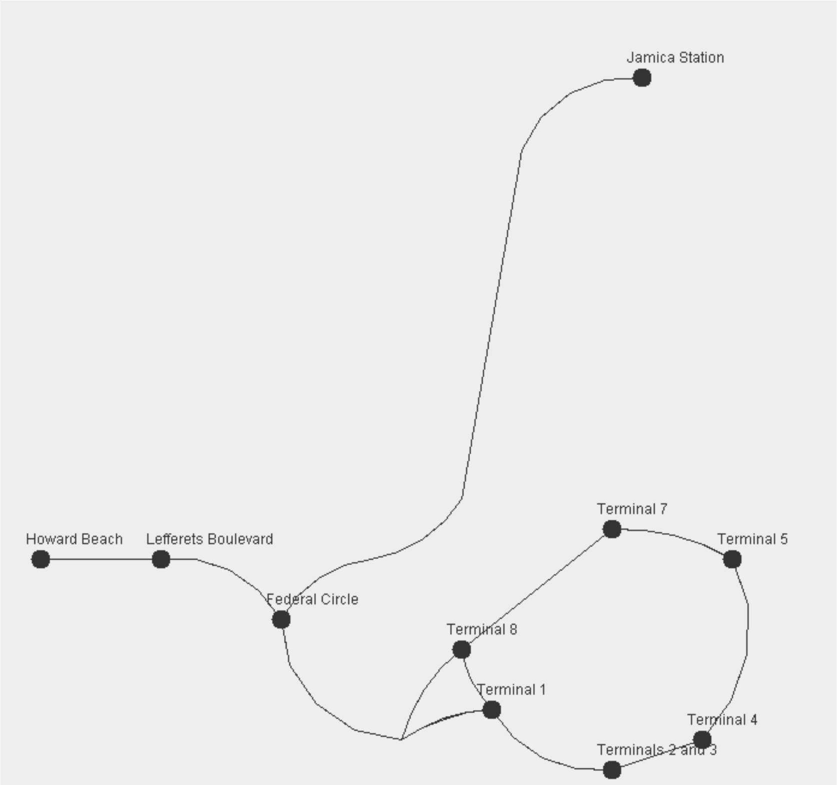


Figure 3.1.2: APMSM Networkvisual of Airtrain JFK

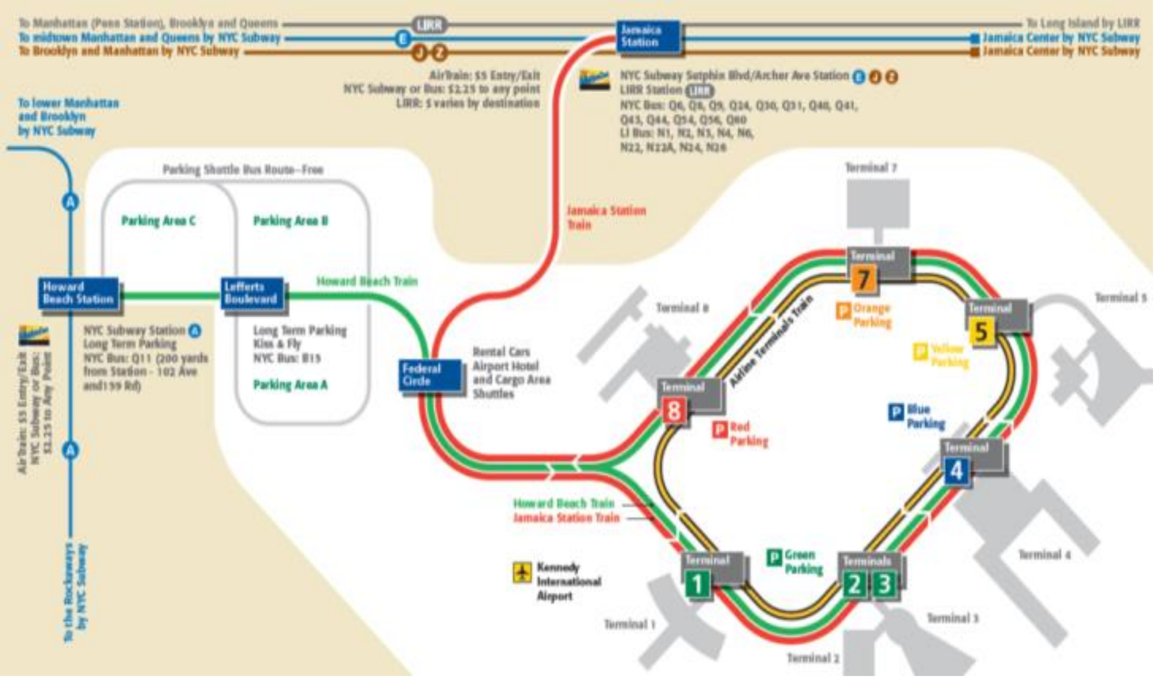


Figure 3.1.3: Official Airtrain JFK Map
Source: Port Authority New York New Jersey (2011)

Many scenarios simulated had multiple service routes just as Airtrain JFK shown above. This was modeled in APMSM by creating routes. Routes are an ordered group of stations and have an assigned headway in seconds. The headway for single route systems was two minutes, which is comparable to the high speed medium capacity Vancouver Skytrain system (Translink, 2013). If two routes used some of the same track, each routes' headway was set to 4 minutes and the initialize2 command was used to make one of the route's trains operate exactly halfway in between the other route's trains. After the routes were coded, the network and train specifications were inputted. The specifications were based on a six-car Bombardier Innovia Metro 300 train and remained constant throughout each of the scenarios (Bombardier, 2011). The specifications included:

- Simulation run time: 1 hour or 3600 seconds
- Acceleration rate: 1.00 m/sec^2
- Capacity: 804 passengers per train (134 passengers per car x 6 cars)

- Brake rate: 1.00 m/sec^2
- Dwell time: 35 seconds
- Diffusion rate:36 passengers/seconds ($6\ cars \times \frac{3\ doors}{car} \times 2\ \frac{passenger}{door\ seconds}$)
- Maximum speed: 27.77 m/sec (100 km/hr)

Next, the scenarios were initialized by having the simulation release a single train for each route one at a time, all while collecting the travel time between each station. The simulation used this information to calculate how many trains were needed for each of the scenarios' routes and which route was the best route for each origin destination (OD) pair. Each route was assigned a fleet of trains based on the route's designated headway. The headway was decreased to an effective headway so when the simulation divided total travel time by the headway to calculate the fleet size, the resulting number is an integer. OD pairs refer to the set of passengers going from one origin to a specific destination. If multiple routes covered the same OD pair, passengers would use the fastest route and any other route which travel time exceeded the quickest route by below the user specified threshold (1 minute). Finally, the hourly passenger demand for each OD pair was set for each scenario. A sample of the code can be seen in Appendix 1.

3.1.2 APMSM Mechanics

Each simulation began with the initialization process. For all the scenarios' routes, a train was sent from the depot through all its stations. The trains' movements were controlled using a series of rules shown below in Figure 3.1.4.

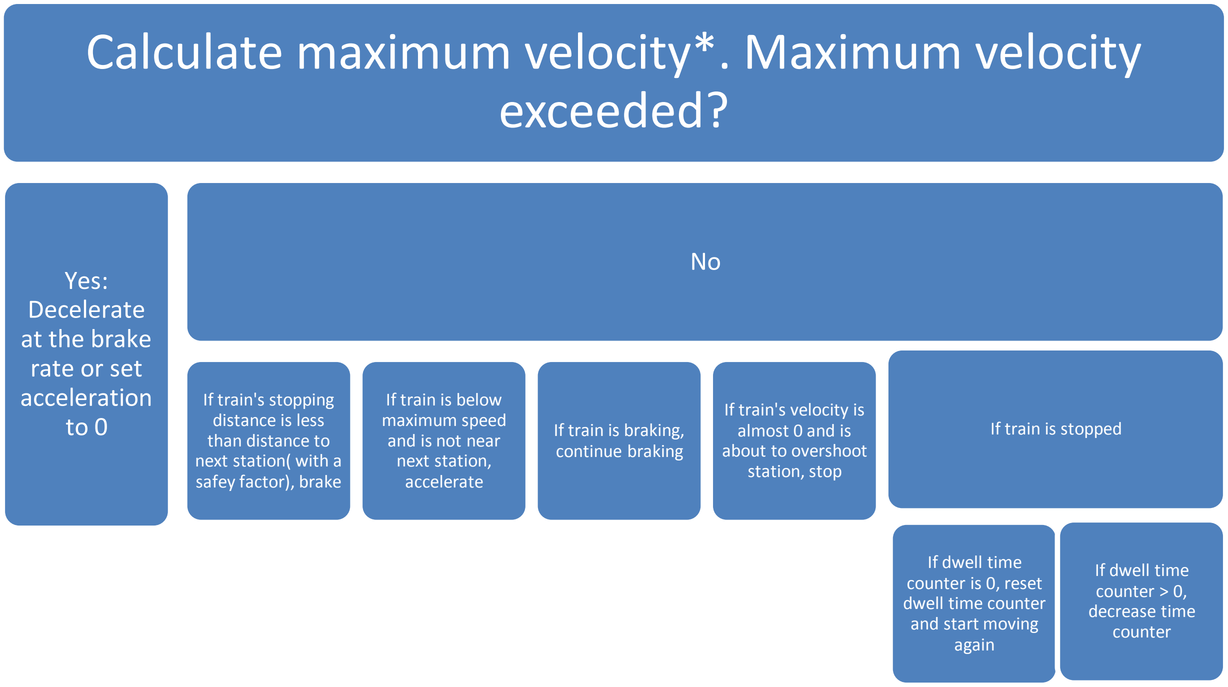
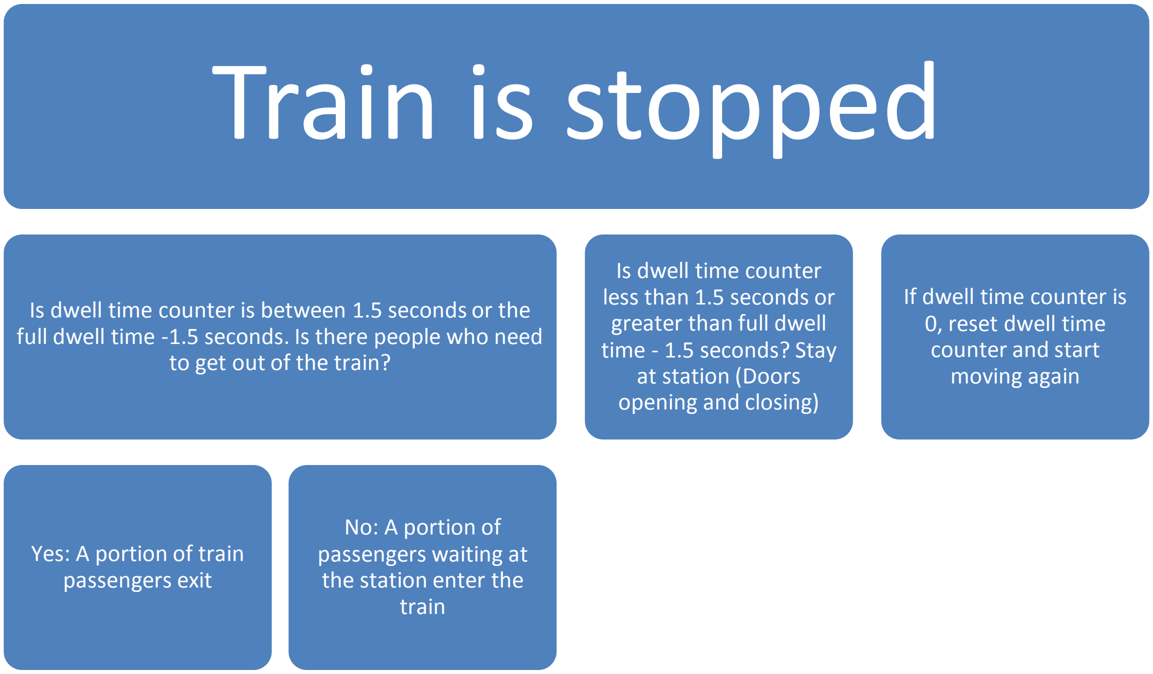


Figure 3.1.4: Train Movement Rules
***If train is on curve, maximum velocity is calculated using equation 26.16 from Hay (1982)**

While each train moved through the network, the simulation collected what time trains arrived at each station (arrival to arrival). Once the train arrived at the first station of the route for the second time, the train was removed from the system. The model calculated an effective headway below the original headway based on the time it took the train to move through the route. The initialization sequence created enough trains to support the effective headway. Using this headway, the model assigned a start time to each train. This start time was adjusted in case the initialize2 command was used. The run sequence began with each train leaving the depot based on their assigned start time, ensuring that the trains were correctly spaced. Before the official run sequence began, the simulation waited until all the trains were released from the depot. The trains moved similarly to initializer trains with additional rules for stopped trains. See Figure 3.1.5 for an overview of additional rules.


Train is stopped

Is dwell time counter is between 1.5 seconds or the full dwell time -1.5 seconds. Is there people who need to get out of the train?

Is dwell time counter less than 1.5 seconds or greater than full dwell time - 1.5 seconds? Stay at station (Doors opening and closing)

If dwell time counter is 0, reset dwell time counter and start moving again

Yes: A portion of train passengers exit

No: A portion of passengers waiting at the station enter the train

Figure 3.1.5: Additional Dwell Rules for Run Sequence

The simulation could allow each train to go through a vehicle detection sequence that senses if there is a vehicle in front, but this feature was disable in this thesis since the simulation perfecty spaces vehicles and the operation was assumed to have no problems. After the simulation ran for the set period of time (run time), the trains continued to operate until all passengers reached their destination. After the run time was reached, the trains continued to operate and record travel time, but all other simulation functions (wait time, passenger arrival, etc.) were disabled, which prevented any skewing of the results. The entire simulation took about 14 seconds to complete all the steps if all features were enabled. Disabling the vehicle detection sequence and output file generation sped up the process considerably.

3.1.3 APMSM Output

APMSM outputted data in three locations: the Java console, the initializer text file, and the train text file. The java console output contained information also included in the text files, but the console output could be seen immediately after the simulation and did not require any processing. The console information included a plethora of information, but most importantly, the average wait time and average travel time. The initializer text file showed the initialization trains' activities, the travel time between each OD pair for each route, the direction between each OD pair for each route, the minimum travel time between each OD pair, and the acceptable directions between each OD pair. The train text file showed the same information from the console in addition to the trains' activity through the simulation and residual passengers waiting at stations. When a completely new network was created for the thesis, all data sources were reviewed to ensure their integrity, but when there were only minor adjustments, the console was the only data source reviewed.

3.1.4 APMSM Assumptions

There are many assumptions built into APMSM that simplify the modeling process including:

- Stations and vehicles are represented as points
- The system is two dimensional, the vertical component is neglected
- Vehicles have constant acceleration
- Trains operate perfectly (no breakdowns)
- Passenger arrival is deterministic
- Passengers are aggregated and when they move between stations and trains, an equal proportion of passengers with the same origin/destination are moved between stations and trains
- For this thesis, intersections between other track sections were grade separated

All of the above assumptions differ to how automated people movers really operate, but provided a good enough approximation for this thesis.

3.2 PRT Simulation Methodology

BeamED, developed by Beamways AB, was the simulation tool utilized to model PRT. BeamED allows users to draw a PRT network out of different elements by simply clicking on a graphical user interface (GUI). These elements can be expanded or shrunk with simple key strokes and any expansion or contraction to each element is reflected in the GUI. System characteristics such as number of vehicles and maximum speed can be input in the setup menu. Demand is specified with multiple techniques including an automatic population based demand synthesizer, an OD table, or a land use based demand synthesizer. Once the simulation is activated, it only takes a few seconds to model an hour's worth of PRT operation. The model assumes two-dimensional operation, deterministic passenger arrival, and perfect performance just as APMSM. BeamED outputs data in a window after the simulation, through the elements on the GUI, and on a spreadsheet stored in a separate file.

3.2.1 BeamED Input Requirements

To start each scenario, the network was drawn on the GUI. See Figure 3.2.1 for a screenshot of the GUI.

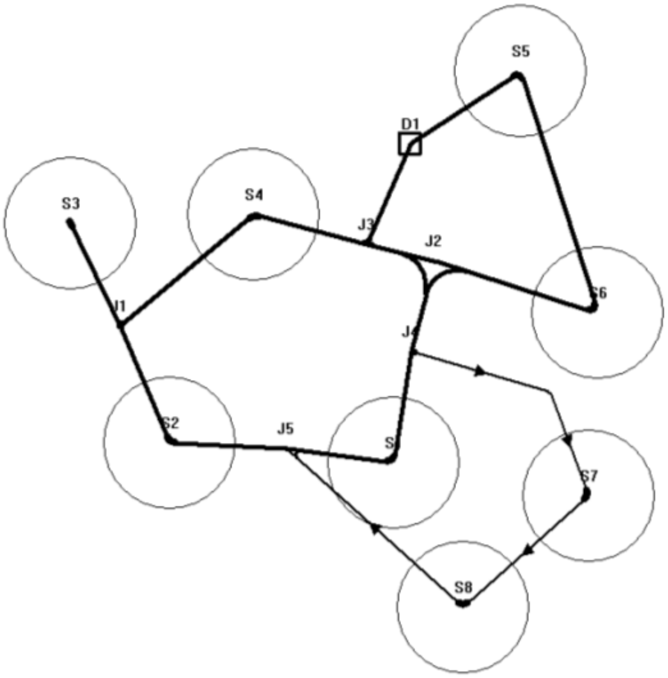


Figure 3.2.1: BeamEd Screenshot

BeamEd has many built in components that allowed any scenario to be created. First, the stations (S1, S2, …) had to be drawn. Berths may be added to stations until it was geometrically impossible, but for this thesis, only 30 berths were used. These stations were next connected with guideway, which can be bidirectional as seen throughout most the sample system or one-way like the section between J4, S7, S8, and J5. Depots (D1) needed to be placed for vehicles to spawn from. Depending on the scenario's geometry type, junctions or curves could be created from existing guideway sections with adjustable radii (Gustafsson, 2012).

After the scenario's PRT network was finalized, the settings on the project setup menu were finalized. Similar to the APM vehicle characteristics, most of the settings stayed static for all the scenarios. The settings were based off BeamED's recommendations and practice, which included:

- Minimum allowable headway: 3 seconds
- Vehicle capacity: 4 passengers per vehicle
- Velocity: 15 m/s (54 km/hr)

- Acceleration: 2.4 m/s^2
- Vehicle count: As needed
- Simulation run time: 1 hour or 3600 seconds
- Mean group size: 1.5 people per group

Although the upcoming Amritsar PRT will feature six-person vehicles, four-person vehicles were used since they represent the industry standard (PRT Consulting, 2011). Demand was one of the thesis's settings that shift scenario to scenario. The simulation software has three techniques to input demand. To implement the simplest method, only the population near the PRT and the percentage of population that use PRT is needed. BeamEd automatically divides the population proportionally based on the number of berths located at the station. This technique provides a quick assessment of PRT, but does not take into account the type and magnitude of activities around each station. Another method that can be utilized is inputting a demand matrix with the number of riders between each station (OD Matrix). A demand matrix multiplier can be applied to change the magnitude of the matrix if each cell in the matrix remains proportional to one another. Lastly, GIS data can be utilized to estimate ridership based on the amount of different population types (residential, work, shopping) in each GIS polygon. For this thesis, the matrix technique was used because it allows the greatest control over demand levels (Gustafsson, 2012).

3.2.2 BeamEd Procedures

Less was known about the BeamEd procedures compared to APMSM since the simulation code was unavailable to the public, but some of the important aspects of the simulation were available. For most of the scenarios, BeamEd only took a few seconds to run, but if the scenario was overcapacity, the system took longer to simulate. Through the course each simulation, the scenarios' stations were assigned an ideal number of empty vehicles dwelled based on the anticipated demand and the simulation would redistribute the vehicles around the scenarios' stations to match the ideal dwelled vehicle count. BeamEd used a pseudo dynamic traffic assignment technique for vehicle route assignment where vehicles follow the shortest path to their destination, which BeamEd recalculated every virtual five minutes for each origin destination (OD) pair. BeamEd kept track of statistics throughout the simulations except during the initial period of the simulation, when the system was stabilizing. The simulation behaved similar to Group Rapid Transit (GRT). If there were not extra vehicles at a station, passengers with the same destination were modeled to share the same vehicle, though this happened more during scenarios with heavy loads (Gustafsson, 2012).

3.2.3 BeamEd Output

BeamEd has three sources of information, a window that displays after the simulation finishes, the simulation network itself (result display) and a spreadsheet. The window provides a quick overview of network geometry, network performance, vehicle performance, and passenger delay. The result display shows the performance of the simulation network and how each component performs during the simulation. A sample result display output is shown below in Figure 3.2.2.

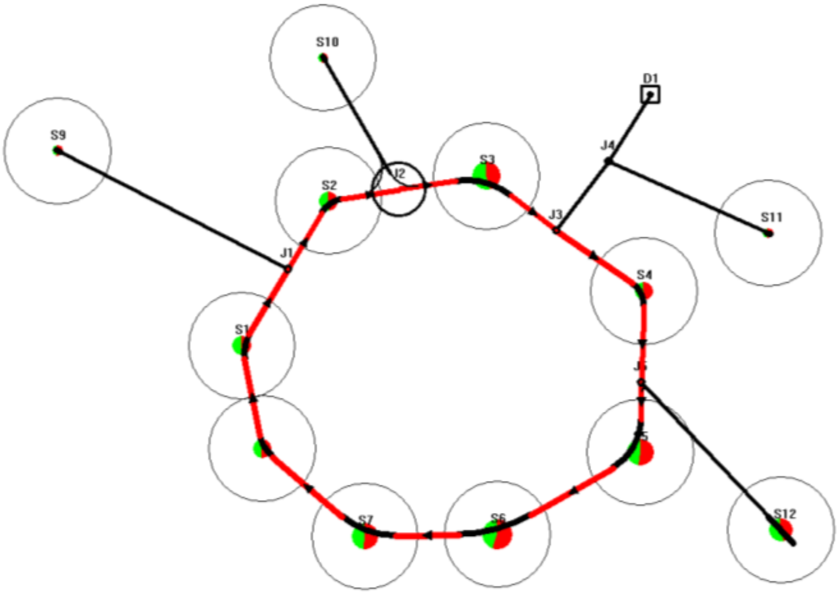


Figure 3.2.2: Sample Result Display

The thickness of the guideway sections represents the usage of the tracks. If they are colored red, the usage is above half the capacity. Each station has a corresponding pie chart. The larger the chart, the greater the station usage was. For each of the pie charts, red and yellow represent the ratio of arrivals and departures respectively. The cursor may be moved over the station area to obtain station specific information such as number of berths, maximum number of passengers waiting, or the number of arrivals per hour. Junctions are not full designed before the simulation starts, but after the simulation trial, the model will show what type of junction should be constructed for each intersection. If the junction is not too busy, it can be built as a roundabout as shown by a circle (J2). If the junction has higher volumes, it should be built as a cloverleaf, which is represented as a 3 or a 4 depending on how many legs the junction has. The spreadsheet displays the same information as the window with the addition of many origin and destination matrices including travel time and average speed. For this thesis, the average wait time from the window and travel time matrix from the spreadsheet were the most pertinent information.

3.2.4 BeamEd Assumptions

Multiple assumptions were made in the mechanics of BeamEd. They include:

- The system is two dimensional, the vertical component is neglected
- Trains operate perfectly (no breakdowns)
- Passengers share vehicles if they have the same destination and if there is a queue
- Group size is based on discretized Poisson Distribution with selected mean
- Arrivals are deterministic, but pulse arrivals can be programed

3.3 Measures of Effectiveness

The main measure of effectiveness (MOE) for the thesis was average trip time. Average trip time is the sum average wait time and average travel time, which are both outputs from each of the simulation programs. Decision makers choosing which mode to implement for a new transit project consider the lifecycle costs, reliability, and environmental impacts in addition to trip time. These other MOEs were not considered because they were either too system-specific or about the same between APM and PRT.

Lifecycle costs, which include capital and annual costs, are generally the most important MOE to decision makers, especially when budgets are limited. Cost greatly varies based on the location of a transit system. Capital and annual costs depend on:

- Material expenses- Material expenses can vary by location
- Terrain/environment of the project- The terrain/environment can require certain additions(tunnels, viaducts, bridges, site remediation, traffic impact mitigations, etc.) that greatly increase the cost
- Project’s jurisdiction’s code/laws: Labor laws, building codes, document requirements, and the permitting process varies by the nature and location of the project

- Labor costs: Labor costs vary considerably region to region

All the above factors contribute in making an APM or PRT system with the exact same alignment cost much different in one location verses another. Per mile and station costs estimates are available such as the figures used in Juster and Schonfeld (2013), but PRT is overwhelmingly less expensive. See Chapter 6, Application, for a cost comparison of two actual systems.

Service reliability, defined here as the percent of time the system operates without an operational problem, is another important MOE. If a system does not work when it is needed, there is little reason to build it. Reliability is high dependent on the quality of the system's construction and how well a system is maintained. Both APM and PRT have proven to operate with reliabilities above 99% (Long, 2011; TransLink, 2011). Since both modes are extraordinarily reliable, there was not a reliability difference to compare for each scenario.

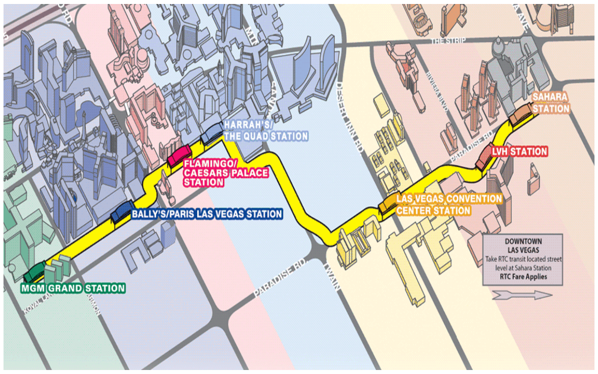
In terms of environmental impacts, both PRT and APM use about the same amount of energy, but what environmental impacts are considered is contingent on a transit project's location. An automated guideway transit system located in a busy downtown area would need to be designed to minimize the visual impact, while a system in a suburban center filled with homes would have to attempt to minimize noise. For an exterior airport automated guideway transit systems, noise or visual impacts are generally not considered.

Chapter 4: Simulation Trials Description

Multiple simulations were performed to model what type of systems would appear in airports, specialized activity centers or urban areas. Multiple system designs types were analyzed and cover a spectrum of alignment designs and magnitudes. The demand levels and distributions were adjusted to cover a wide range of situations. The various geometric and demand situations were combined to form final testing scenarios for both APM and PRT.

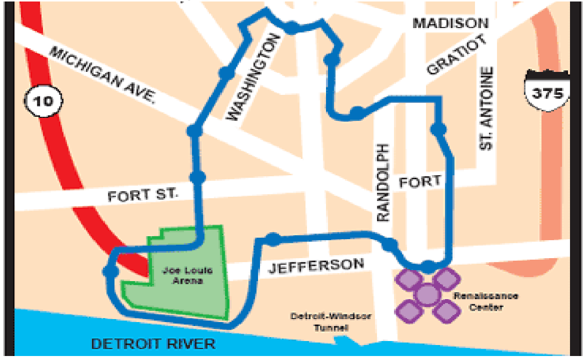
4.1 System Design Types

The first and simplest design type was dual lane, which is fundamentally a linear route. Notable linear routes include Atlanta Airport's Plane Train, Dubai Metro's Red Line, and the Las Vegas Monorail. These types of routes may be component within with a larger network, but linear routes operate independently on their own right of way. The Y-type of route resembles a linear route, but has another segment that branches out usually towards the end of the route. The London Heathrow PRT, Copenhagen Metro, and the Canada Line of the Vancouver Skytrain system all resemble a Y-type system. The Y-type system features two routes that share tracks on part of their journey, but diverge on one end of track to go their separate ways. The loop type of system appears to be a linear route whose ends are connected to form a circle. The Detroit People Mover, Seattle Tacoma Airport's Satellite Transit System, and Dallas Fort Worth Airport's Skylink are all loop systems. Some loop type routes are bi-directional and others are one-way. The last type of system was loop with legs and looks like the loop system with branches out the loop. Notable loop with legs type system include the Airtrain JFK, Miami Metromover, and the Airtrain SFO. Figure 4.1.1 shows maps for each type of system.



Source: Las Vegas Monorail, 2013
System: Las Vegas Monorail
Type: Linear

Source: Mapsof.net, 2012
System: Copenhagen Metro
Type: Y



Source: Drdisque, 2006
System: Detroit People Mover
Type: Loop

Source: Miami Dade County, 2012
System: Miami Metromover
Type: Loop with Legs

Figure 4.1.1: System Design Examples

4.2 Geometric Alterations

Transit systems vary in how far apart stations or stops are. Local buses may have stops every block, while commuter rail services can have miles between each station. Light rail or heavy rail systems such as the Washington Metro or Miami Metrorail, have station placed close to each other in downtown center, but far apart towards the suburban areas. Transit located in activity centers generally has roughly equidistant station spacing. Transit systems' varying station spacing can be demonstrated by the Miami Metromover APM system and Miami Metrorail heavy rail system shown below in Figure 4.2.1.

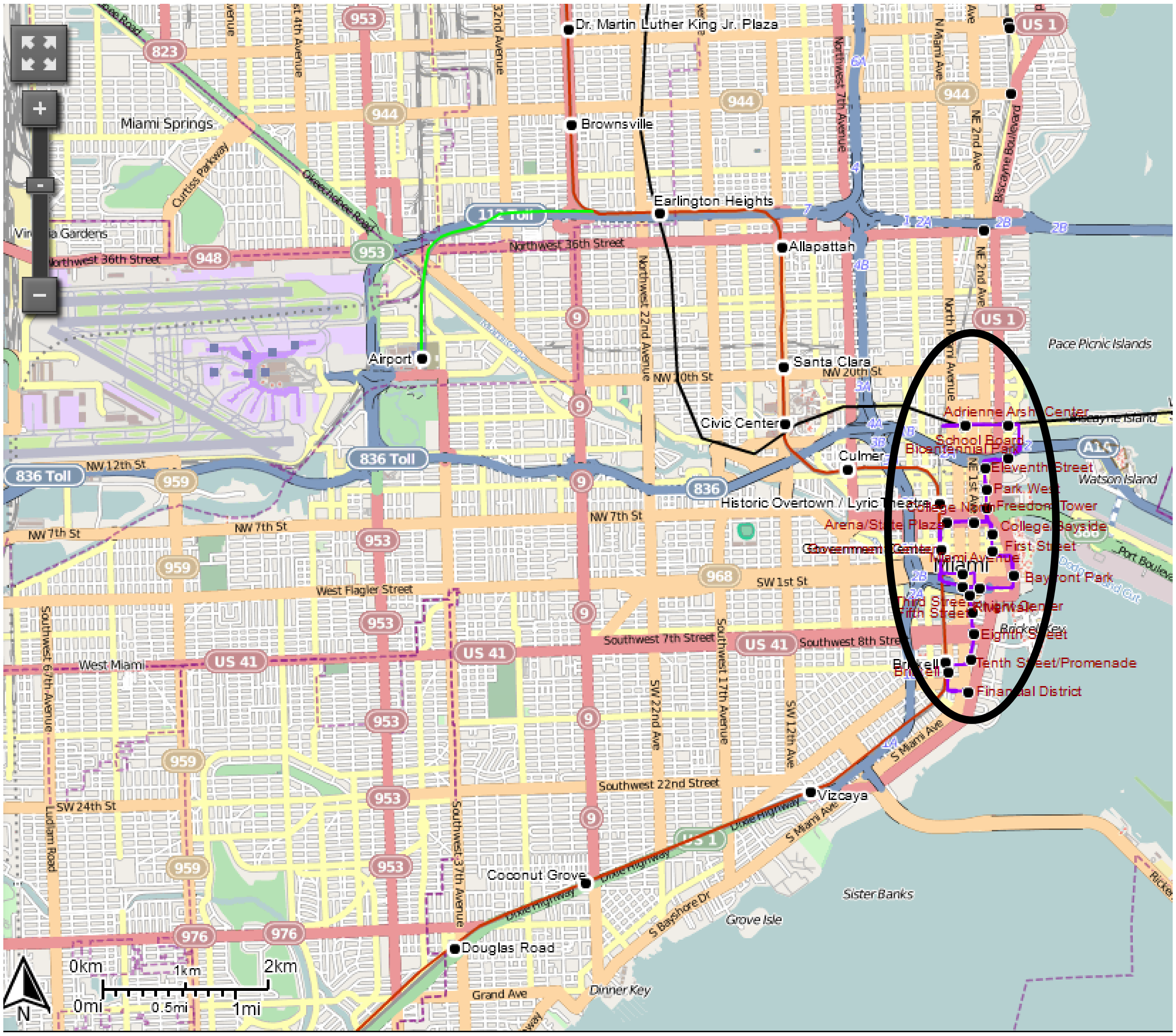


Figure 4.2.1: Miami's Urban Rail Systems
Source: (Sharemap.org, 2013)

Miami has three passenger rail systems including Tri-Rail, Miami Metromover, and Miami Metrorail. Tri-Rail is a commuter system that spans multiple counties and is out of scope for PRT. Miami Metromover, the purple system circled in Figure 4.2.1 and shown on the lower right of Figure 4.1.1, is an APM located in the central business districts of Miami. This system was built to transport people around the busy commercial hub and many of the Metromover passengers feed into the Metrorail system (Brooks, 1989). Metromover stations are very close to each other at about 0.2 miles apart. Miami Metrorail, the red and yellow system that spans Figure 4.2.1, is a heavy rail system that spans Miami-Dade County. It facilitates movement from

Miami-Dade County’s residential areas to the urban core. Metrorail’s station spacing varies from less than half a mile in the downtown area to more than a mile in the more residential areas. For this thesis, each system design was additionally adjusted by increasing or decreasing distance between stations (station spacing). For most of the scenarios the stations were equally spaced apart, but in some scenarios, the station spacing varied. This action reflects how different transit systems (Miami Metromover vs. Metrorail) have different station spacing. Stations were spaced 0.25, 0.5, 1, and 2 miles apart. Half the 1 mile station spacing scenarios also varied station spacing to reflect an urban to suburban system such as Miami Metrorail (except loop scenarios) and include 0.5, 1, and 2 mile apart stations all in the same network. In addition, the number of stations per route included 5, 10, and 20 stations per route.

4.3 Demand Levels

Transit systems with the same technology generally have the same capacity, but have quite different utilization. Table 4.3.1 shows a few different transit system and statistics about their utilization.

Table 4.3.1 Transit System's Daily Boardings per Station

System	New York Subway	Washington Metro	Miami Metromover	Vancouver Skytrain	RTD Light Rail (Denver)	MBTA Green Line (Boston)
Type	Heavy	Heavy	APM	APM	LRT	LRT
Number of Active Stations	420	86	20	33	34	68
Average Weekday Usage	12583	8651	1533	7,656	2009	2618
Median Weekday Usage	7047	6532	903	5,596	1501	1564
Minimum Station Useage	116	1543	229	805	235	86
1st Quartile Useage	4173	4259	540	3171.5	553	810
3rd Quartile Useage	13648	10379	2091	11136	2661	3307
Maximum Station Useage	189426	33697	8333	24,982	8799	13488
Source and data's year	Metropolitan Transportation Authority (New York), 2011	Washington Metropolitan Area Transit Authority, 2011	Miami-Dade County Transit, 2011	British Columbia Rapid Transit Company, 2011	RTD, 2011	MBTA, 2008

The data from Table 4.3.1 was used as a baseline to choose the demand level for the scenarios, though some of the data needed clarification. The New York Subway has by far the heaviest station utilization, but many of the stations have more than two tracks (New York Metropolitan Transit Authority, 2012). For this reason, New York's maximum value was ignored. Washington Metro features multiple platforms at its transfer stations, but Washington's busiest station only has two tracks and was considered (Washington Metropolitan Area Transit Authority, 2012). Each scenario was modeled for a virtual hour and necessitated that daily demand figures be converted into peak hour demand. To covert the daily station demand to peak hour station demand, the average ratio of peak hour volume over daily volume from Washington Metro's peaking data (0.2) was multiplied with each station's daily demand (P2D, 2008). Based on Table 4.3.1, the clarifications, and the peak hour ratio, the demand levels were selected, and are shown in Table 4.3.2.

Table 4.3.2: Scenario Demand Levels

Loading	Daily Passengers	Peak Hour Passengers
Very Low (Miami Metromover)	1000	200
Low (Light rail)	2500	500
Medium (Skytrain)	5000	1000
High (Heavy Rail)	7000	1400

4.4 Demand Distribution

For the scenarios with equal station spacing, the same peak hour passenger levels were used for each station. When there was unequal station spacing, additional demand was allocated based on a typical suburban to urban morning commute pattern. The stations that were 2 miles apart would be considered stations on toward the edge of the system and have mostly passengers commuting elsewhere in the morning. The stations 1 mile apart were considered suburban stations with passengers commuting to and from the station in the morning. Stations 0.5 miles apart were considered urban core stations that mostly draw in morning passengers. Using Washington Metro OD information for morning commutes, another OD table was created , as seen on Table 4.1.1., with the median number of passengers for a given combination of edge (E), suburban (S), and urban (U) origin destination combination (P2D, 2008).

Table 4.4.1: Washington Metro Median Outer Suburban Core Origin Destination Combination

	Destination			
Origin		C	S	E
	C	25.91	6.36	2.55
	S	35.64	2.41	7.20
	E	53.09	10.00	3.50

To compute the final OD numbers for the unequally spaced stations, the following equation was used.

$$X_{OD} = \frac{T * D_{OD} * M}{\sum_{A=C,S,E} \sum_{B=C,S,E} N_{AB} D_{AB}}$$

X=Number of Passengers for a certain origin (O) and destination (D)

T=Total number of passengers in the system (=Number of stations * 200)

D=Demand from Table 4.1.1

N= Number of the OD type in the system

M= Multiplier (1, 2.5, 5, 7 depending on if the base number of passengers per stations is 200, 500, 1000, or 1400)

4.5 Combining Variables

Combining all the possible independent variables led to the creation of 208 scenarios. Each scenario was tested on both the APM and PRT simulation. See Appendix 2 for all the scenarios and their results.

Chapter 5: Simulation Results

The results are displayed below using a graph matrix for each system design. Due to space constraints of the graph matrices, the legend, axes labels, and graph title are taken out of each graph. A sample of a graph with the missing information is shown below in Figure 5.0.1.

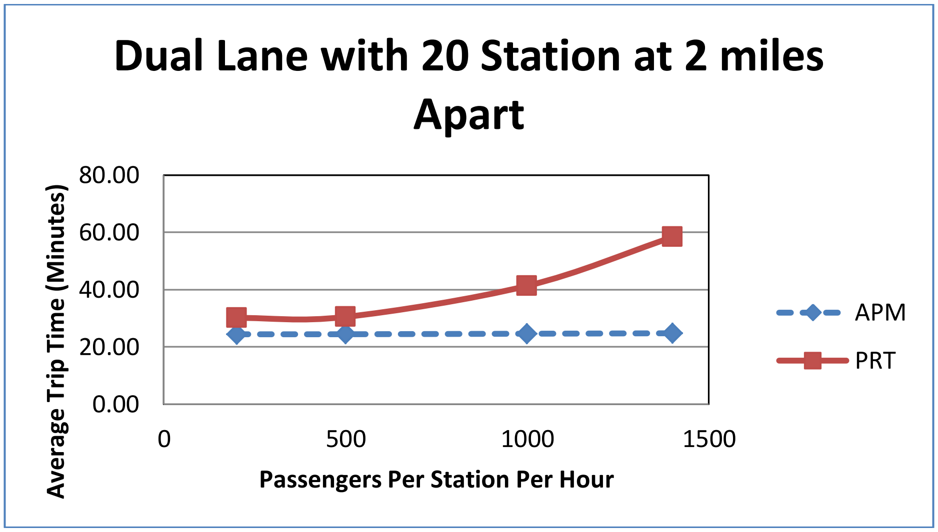
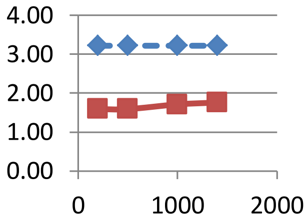
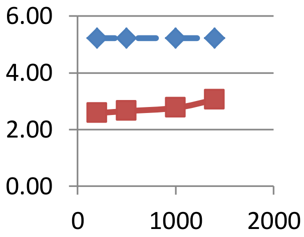
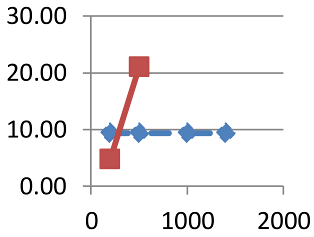
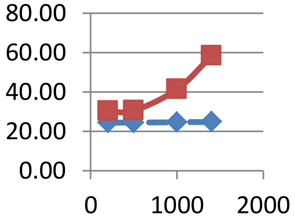
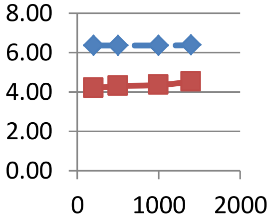
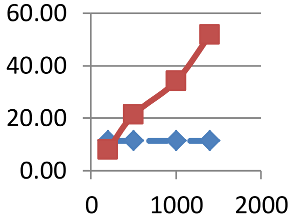
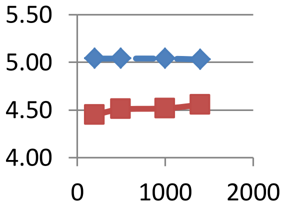
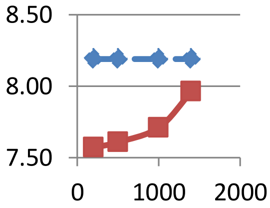
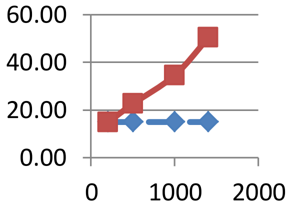
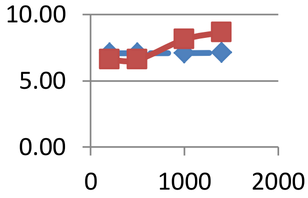
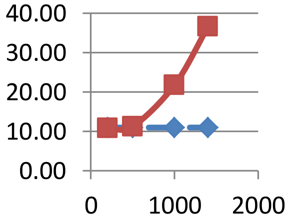
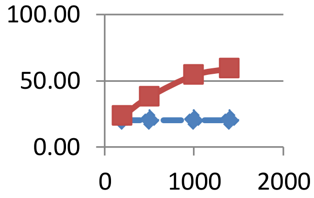
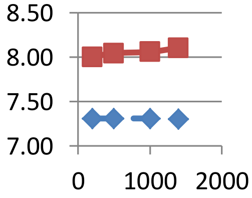
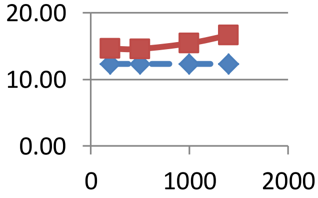
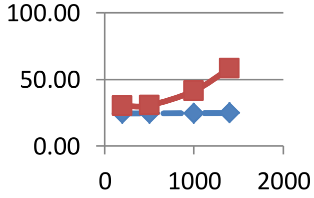


Figure 5.0.1: Results Graph Example

The x-axis represents passengers per station per hour and the y-axis shows average trip time per passenger. The dashed line with diamonds symbolizes APMs while the solid line with squares represents PRT. Since the distances between stations and number of stations were also varied, the graphs within each of the system design's matrix are arranged accordingly. Each row of graphs has the same spacing between stations and each column had the same number of stations.

5.1 Dual lane

Table 5.1.1 Dual Lane Graph Matrix

	5 Stations	10 Stations	20 Stations
0.25 Mile Station Spacing			
0.5 Mile Station Spacing			
1mile Station Spacing			
Variable Station Spacing			
2 Mile Station Spacing			

As the distance between stations increased, APM tended to have shorter trip times compared to PRT since APMs had a quicker maximum speed. APMs also tended to have shorter trip times compared to PRTs in systems with more stations since APMs' quicker speeds assisted passengers traveling longer distances and APMs' greater capacity could handle the increased number of passengers from the additional stations. PRT's time advantage shank as the number as the passenger demand per station grew. An extreme example of this trend was with the 20 station system with 0.25 miles between each station. PRT was much quicker than APM with 200 passengers per station, but the time advantage eroded so quickly, that the 1000 and 1400 passengers could not be practically modeled for PRT (thus not appearing on the graph). PRT likely failed in this system with higher passenger counts because the tracks were saturated with vehicles. Systems with larger spacing between stations had more room for more vehicles. Figure 5.1.1 shows the flow of PRT vehicles (and passengers in APM's case) for the dual lane configuration.

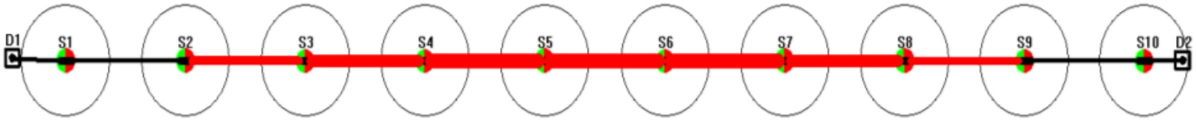


Figure 5.1.1: Dual Lane Configuration Flow

As a general trend, the middle of the system was the busiest location since any passengers trying to move from one half of the system to the other half had to go through the center. In PRT's case, this resulted in congestion of the guideway and for APM, the vehicles themselves became more crowded.

When the unequal station spacing systems were modeled, APM generally performed better. That was because APMs' greater capacity can accommodate the unidirectional flow of the suburban to urban commuting pattern seen in Figure 5.1.2, which concentrated passenger flow towards the urban stations.

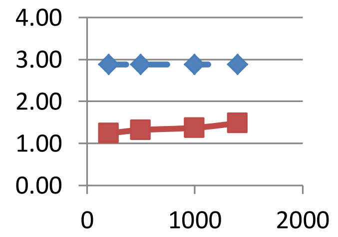
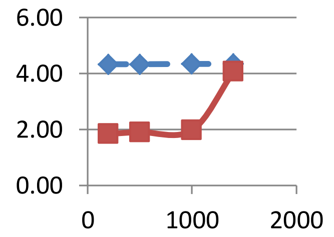
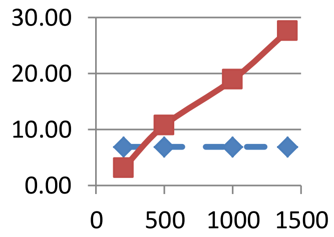
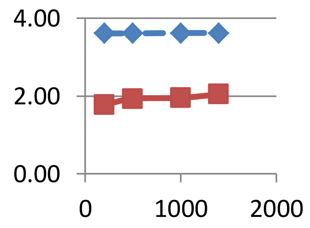
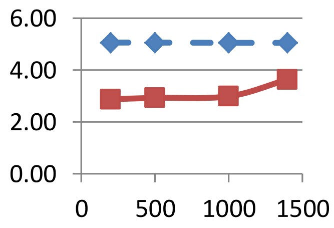
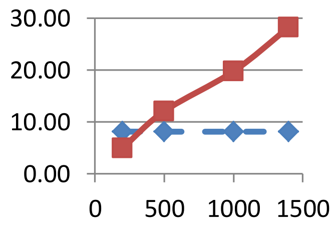
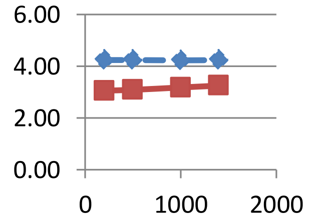
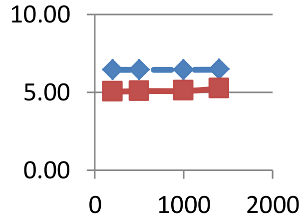
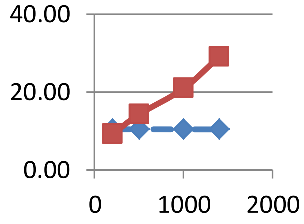
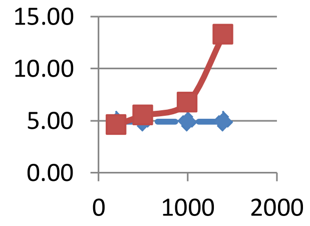
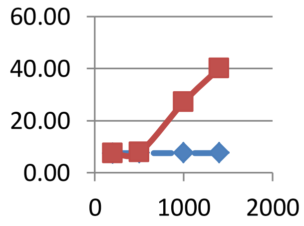
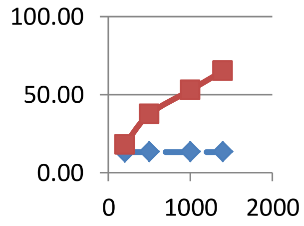
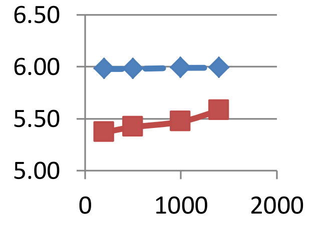
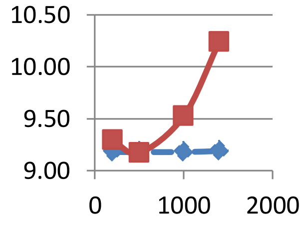
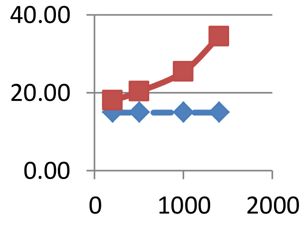
Figure 5.1.2: Dual Lane Unequal Station Spacing Flow

Moving left to right from the edge stations towards the urban stations, the route became congested (i.e., volume approached capacity) by the third edge station. Some of the congestion was relieved by the start of the suburban stations as some of the edge passengers exited at suburban station. This relief was temporary and by the last suburban station, congestion reappeared. Most of the congestion was relieved after half of the urban-bound edge and suburban commuters exited at the first urban station.

5.2 Y

All the Y configuration systems had one fifth of the stations in the stem and two fifth of the stations in the branches which were spaced thirty degrees apart. Since the branches were almost parallel and movement between the branches required a considerable distance away from one’s destination, there were no passengers that traveled from one branch to the other branch. The APM Y systems required 2 routes to cover all the station. Each route covered the stem and one of the branches. The headway of both routes was 4 minutes to ensure that the headway in the stem had the minimum allowable headway of 2 minutes.

Table 5.2.1 Y Graph Matrix

	5 Stations	10 Stations	20 Stations
0.25 Mile Station Spacing			
0.5 Mile Station Spacing			
1mile Station Spacing			
Variable Station Spacing			
2 Mile Station Spacing			

The Y system configuration performed similarly to the dual lane configuration with APM performing better with more stations (especially with high passenger demand) and smaller spacing between stations, except PRT tended to perform better in the Y configuration compared to APM. This was most likely due to the shorter trip lengths. For the 2 mile 0.5 mile station spacing system, the longest possible trip for a 20 station 2 mile spacing system was 40 miles and 22 miles for a dual lane and Y configuration respectively. The short trip distances made PRT’s slower speeds less of an issue. The traffic flow for Y configuration systems can be seen in Figure 5.2.1.

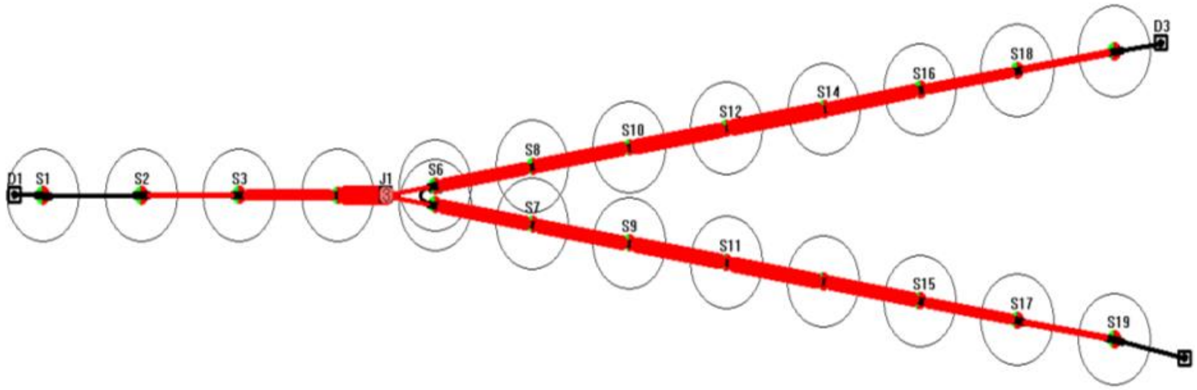


Figure 5.2.1 Y Configuration Flow

The Y configuration tended to be more crowded towards the center system. The most congested region of the Y was where the stem met the junction since the traffic from the two branches created a bottleneck effect. Even though the beginning of each branch was expected to have major congestion as well, those sites only has minor congestion, possible due to the additional capacity of the adjacent junction and the additional capacity of having two sets of tracks for the branches as opposed to the stem’s one set of tracks.

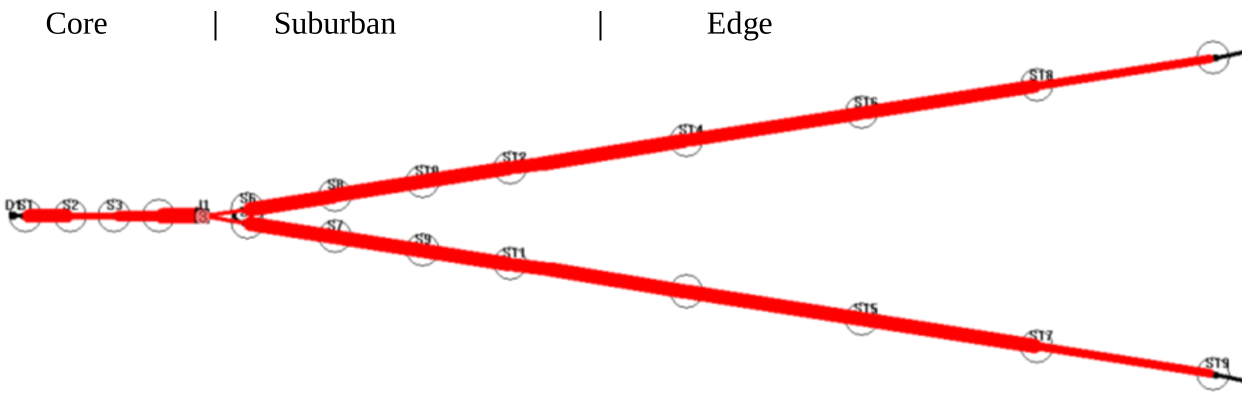


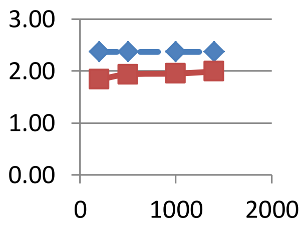
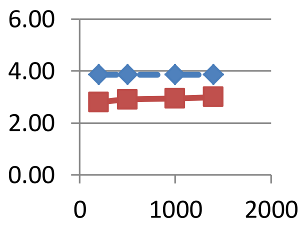
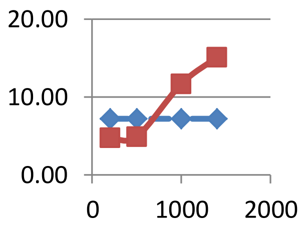
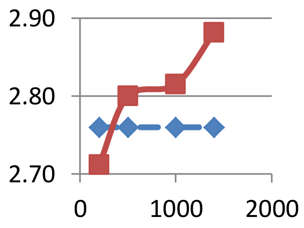
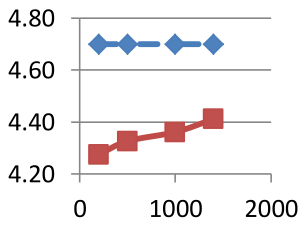
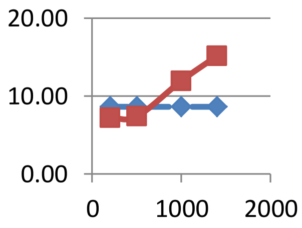
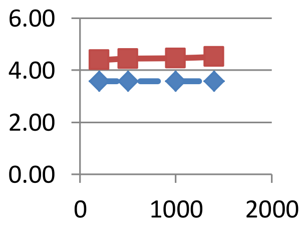
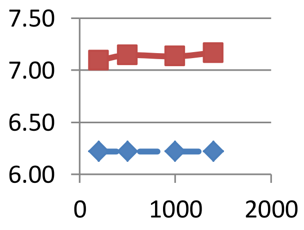
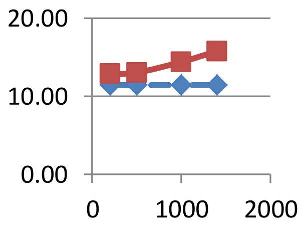
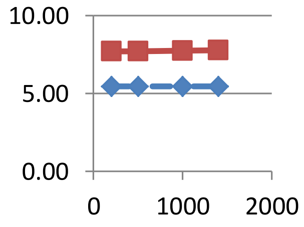
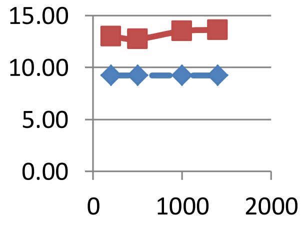
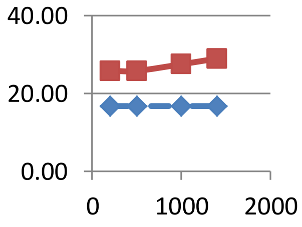
Figure 5.2.2 Y Unequal Station Spacing Flow

Based on Figure 5.2.2, the Y unequal station spacing configuration had congestion at similar locations as the dual lane unequal station spacing system, though the branches at the junction with the stem was less congested than expected.

5.3 Loop

No variable spacing versions of the loop configuration were tested because loop systems generally have uniform spacing. An unequal spacing system was created with the loop with legs configuration. The loop had two routes each with 2 minute headway, one serving all the station clockwise and the other route serving all the stations counter-clockwise.

Table 5.3.1: Loop Graph Matrix

	5 Stations	10 Stations	20 Stations
0.25 Mile Station Spacing			
0.5 Mile Station Spacing			
1mile Station Spacing			
2 Mile Station Spacing			

The loop configuration had lower trip times for both APM and PRT compared to the Y configuration with small station spacing (0.25 & 0.5 miles). This was caused by the greater connectivity and redundancy of having two ways to reach a destination. The loop configuration's time advantage diminished once the station spacing was 1 or 2 miles between stations, especially for PRT which by comparison, tended to perform less favorably compared

APM, which is exemplified when station spacing was 1 or 2 miles and the system had 10 or 20 stations. With these scenarios, PRT performed generally better than APM for the Y configuration, but APM always performed better with a loop configuration. APM performed better than PRT probably because each OD pair tended to have fewer intermediate stations and each OD pair utilized an APM route with 2 minute headways. Figure 5.3.1 shows a 20 station loop configuration. The branches off the loop are depots and do not affect the performance of the system.

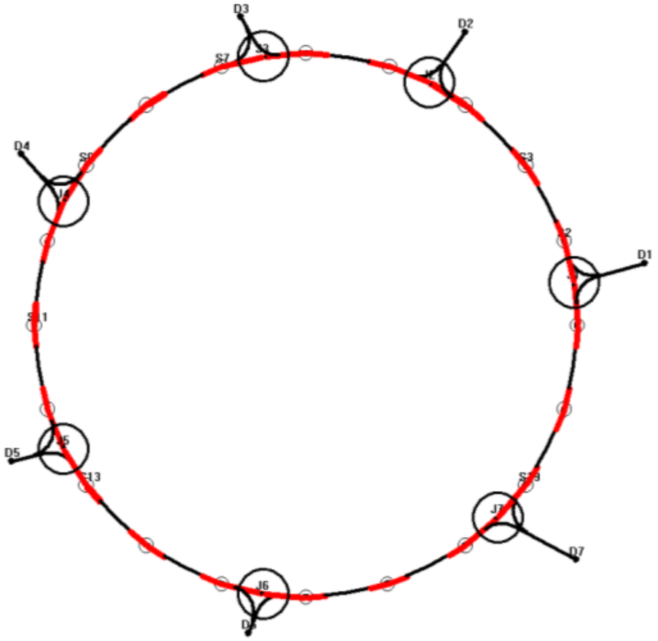


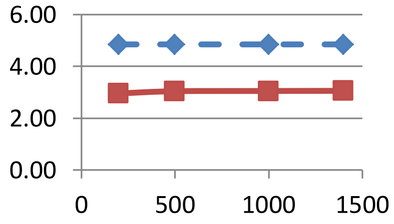
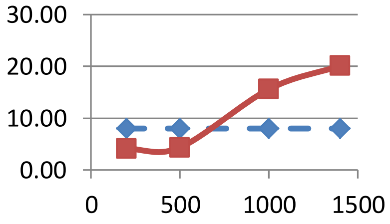
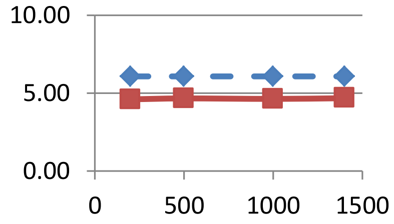
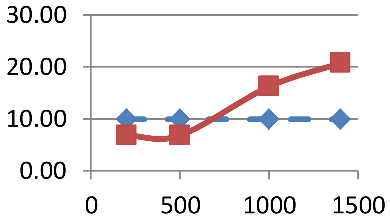
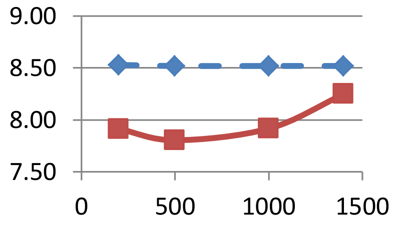
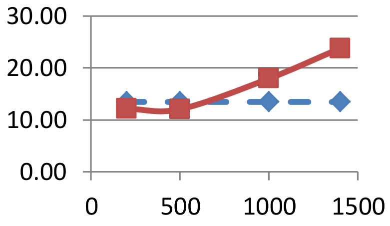
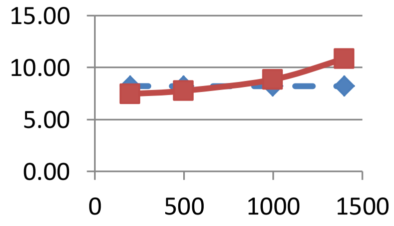
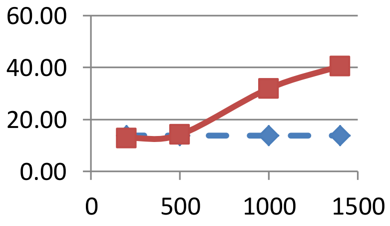
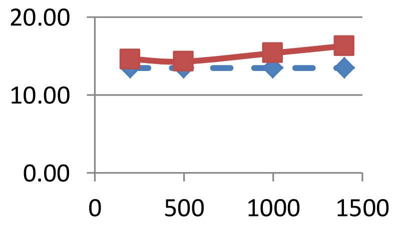
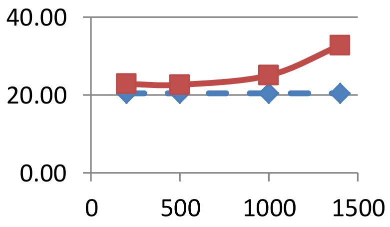
Figure 5.3.1: Loop Configuration Flow

The loop configuration has uniform traffic around the system, which is intuitive since no matter which station is chosen, the system appears identical relative to the station.

5.4 Loop with Legs

The loop with legs configuration was constructed with 4/10 of the stations located in the loop section of the system and 3/10 of the stations located at each of the legs which are 30 degrees apart. There were also two junctions in the loop section spaced the same distance apart as the stations. Five station scenarios were neglected because five stations were too few to create a loop with loop system. Just as the loop configuration, travel between the legs was neglected. There were two two minute headway routes. One that served the stations of one of the branches and the all the loop stations clockwise, and the other route served the other branch and all the loop stations counterclockwise.

Table 5.4.1 Loop with Legs Graph Matrix

	10 Stations	20 Stations
0.25 Mile Station Spacing		
0.5 Mile Station Spacing		
1mile Station Spacing		
Variable Station Spacing		
2 Mile Station Spacing		

The loop with legs configuration was generally slower than the loop and Y configuration, but faster than the dual lane configuration. This configuration favored PRT more heavily compared to any other configuration since the loop leg configuration had the most complexity of any scenario and complexity added redundancy. This redundancy gave PRT vehicles more flexibility when moving throughout the system. Compared to other configurations, loop with leg’s PRT system’s trip time increased at proportionally the slowest rate. The loop with leg configuration flow can be seen in Figure 5.4.1.

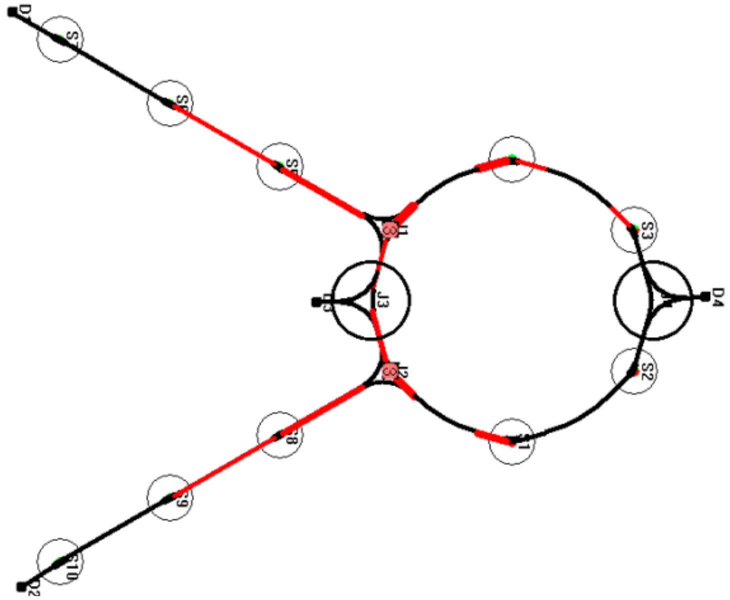


Figure 5.4.1 Loop with Legs Configuration Flow

The loop with leg configuration’s congestion was primarily located where the legs at the loop intersect. An unequal station spacing system can be seen in Figure 5.4.2.

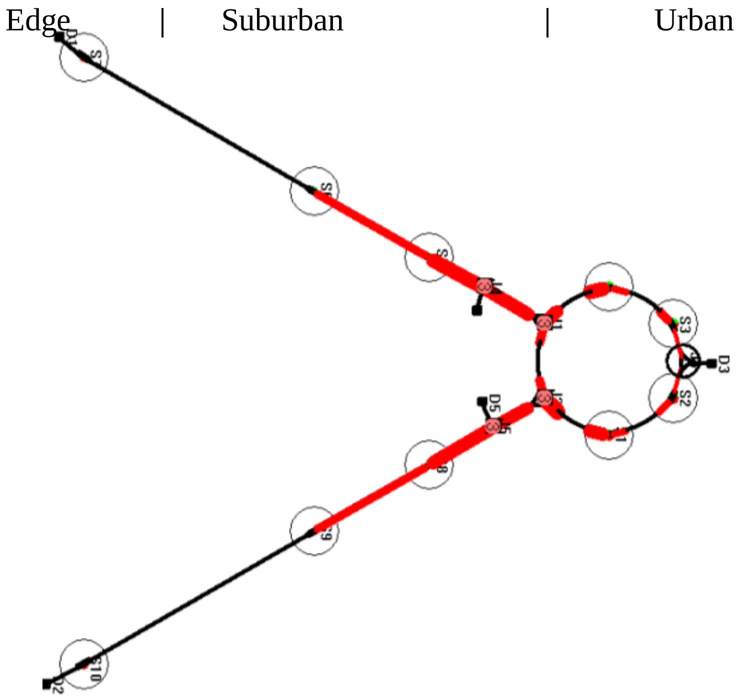


Figure 5.4.2: Loop with Leg Unequal Station Spacing Flow

Compared to other configurations, loop with leg’s unequal spacing system performed more favorability towards PRT, though APM was still the quickest mode for the 1000 and 1400 passenger per station per hour scenarios. As with the equal spacing system, most of the congestion was located where the loop and legs intersect.

5.5 Overall

In the simulations, PRT tended to perform better than APM if the system was complex and had fewer stations closer apart. Longer trip distances from additional stations placed further apart made PRT’s slower maximum speed an obstacle for providing quicker trips. Additional stations do not necessarily make PRTs slower, but the additional passengers from the additional stations without additional system capacity proved to be a problem. If the PRT system is designed with redundant paths for each OD pair such as the system shown in Figure 1.2.1, PRT would be able to increase system capacity. This could be a problem for real-life implementation since extra connections would be extra construction costs.

Chapter 6: Application

The tables generated in Chapter 5 can be used to quickly evaluate whether APM or PRT is the faster mode. Below are two examples of using the tables to choose the faster mode.

6.1 PHX Sky Train

The PHX Sky Train™ is an APM whose first phase opened in April 2013 at Phoenix SkyHarbor International Airport and will eventually connect parking, the rental car center, several terminals, and a light rail line that goes through the Phoenix area. See Figure 6.1.1 for the APM alignment.

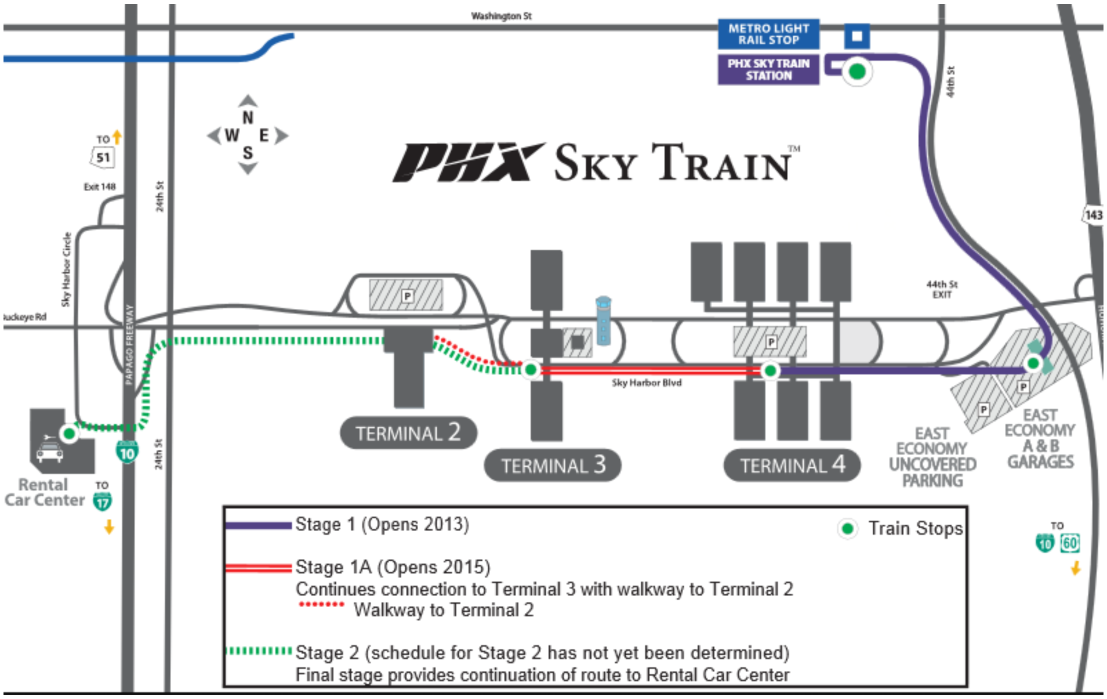


Figure 6.1.1 PHX Sky Train™ Alignment
Source: Phoenix Sky Harbor Airport (2013)

Based off the information and assumptions supplied by Sky Harbor, once the second phase of the PHX Sky Train™ is completed it will (Phoenix Sky Harbor Airport, 2013):

- Be a straight alignment
- Have 5 stations placed about 1 mile apart

- Accommodate 670 passengers per hour during the peak (assuming 8% of daily passengers use system during peak and uniform station demand)

Based off Table 5.1.1, a PRT version of this system will have an average trip time of about 4.51minutes per passenger while the APM version would have an average trip time of 5.04 minutes per passenger. The average trip times are not very different, but when considering that London Heathrow PRT built in a similar environment only cost about $16.2 million per mile and the PHX Sky Train™ is estimated to cost $322 million per mile, PRT's slightly better trip time is an additional advantage beyond the possible cost savings (Juster & Schonfeld, 2013; Phoenix Sky Harbor Airport, 2013).

6.2 Detroit People Mover

The Detroit People Mover is an underutilized APM that opened in 1987, and circulates visitors and workers around Detroit's central business district. A map of the APM can be seen in Figure 4.1.1. Since opening, it has been considered a white elephant (Aitken & Barker, 1989). The Detroit People Mover has:

- A loop alignment (in reality, it is a one-way loop, but for this application it will be represented as if it was a two-way loop)
- 13 stations placed roughly 0.25 miles apart (Detroit Transportation Corporation, 2008)
- 461 passengers per station per day (Milwaukee Daily Reporter, 2011)

Based off Table 5.3.1, the average trip time would be 3.86 and 2.80 minutes per passenger for APM and PRT respectively. Though these two low traffic examples favored PRT, any heavily utilized urban system such as Washington D.C. or New York City's subway would favor APM.

Chapter 7: Post Simulation Analyses

Many assumptions were made when using both the simulations including the maximum velocity and acceleration/ brake rate of the vehicles. Though the capacity of PRT was often exceeded during simulation, all APM scenarios had adequate capacity. These simulated capacities might not have been reasonable to the theoretical or empirical capacities. Travel time and wait time were added together for the results, but demand can affect each type of time differently. In this chapter, the assumptions' effects on the results were tested, different types of capacity for both systems were quantified, and each time's sensitivity to demand was tested for each mode.

7.1 Velocity

A change in the maximum velocity has the potential to affect the results. Greater maximum velocity can decrease travel time, but the magnitude of the change might differ for the two modes. Using the dual lane 10 station variable spacing/demand scenario with 200 passengers per station, the effect of the maximum velocity was evaluated. This particular scenario was chosen because there was only a 13 second difference in average trip time between the modes and the variable spacing will mitigate the influence of station spacing on the results. The results can be seen below in Figure 7.1.1.

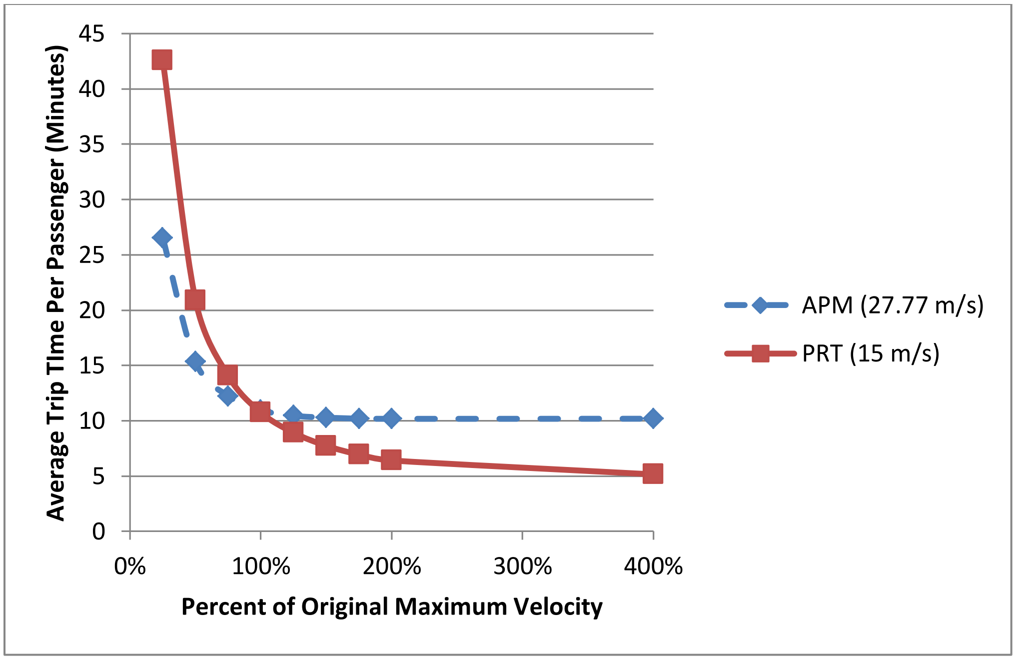


Figure 7.1.1: Maximum Velocity's Effect on Trip Time

Maximum velocity did significantly affect the average trip time per person, but each mode was affected at a different magnitude. Both modes' trip times decreased due to faster speeds, but at some point, this increase was limited by acceleration. If the maximum velocity was high enough, the vehicle did not have enough time to reach the maximum velocity since the acceleration and break rate was not increased with velocity. APM's time advantage with increasing velocities was also limited by the dwell time each station, unlike PRT which does not have intermediate stations to limit the distance within each trip for vehicles to reach the maximum velocity. When maximum velocity decreased, both modes' trip times increase at a higher magnitude than the trip times decreased with increasing the maximum velocity. The increase in trip time was more prominent in PRT since at 50% maximum velocity, APM velocity was 1.85 times greater than PRT and the APM's dwell time became a less significant factor in the overall trip time since the vehicles moved so slowly.

7.2 Acceleration/ Brake Rate

The same scenario used in section 7.1 was used for testing acceleration/ brake rate. The results can be seen in Figure 7.2.1

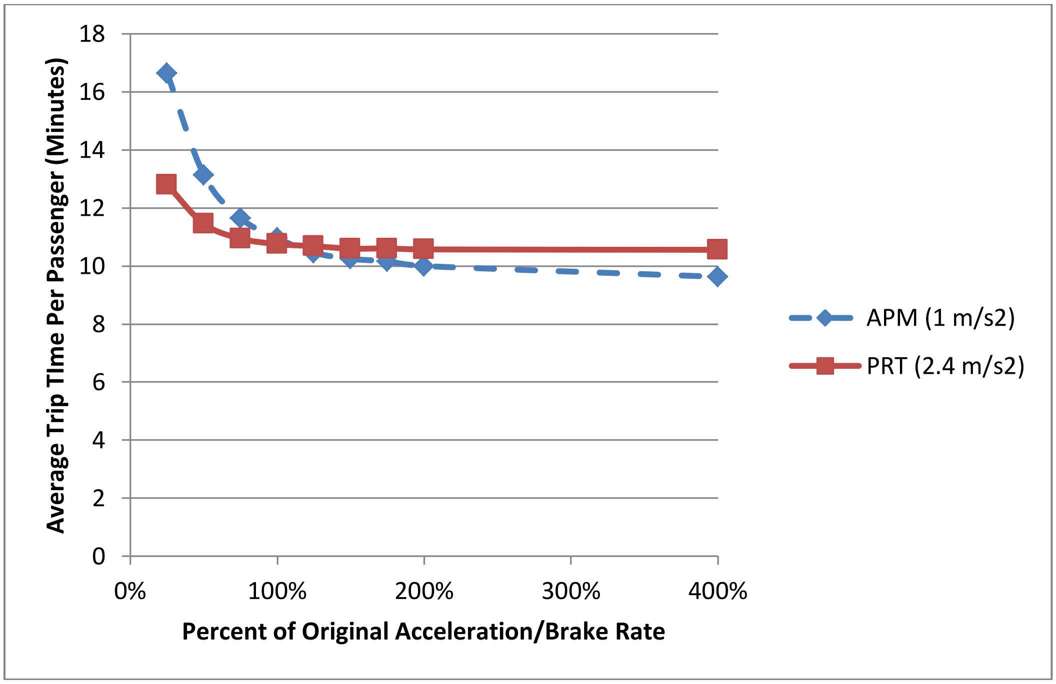


Figure 7.2.1: Acceleration/Brake Rate's Effect on Trip Time

Similarly to maximum velocity, increasing the acceleration/brake rate decreased the average trip time and vice versa. Unlike maximum velocity, APM was much more sensitive to a change in acceleration than PRT because APMs have to start and stop many times for each trip unlike PRT which only has to start and stop once.

7.3 Capacity

Line capacity is the number of passengers in vehicles that can pass through a single point per time unit. There are three ways to estimate capacity:

- Empirical- What the capacity of actual systems are
- Theoretical- Mathematically what the capacity of systems should operate at assuming full loads, and neglecting acceleration and braking
- Simulated- The approximate capacity estimated through simulation

Each type of capacity for APM and PRT can be seen in Table 7.3.1.

Table 7.3.1: Capacities of APM/ PRT (Passengers per Hour per Direction)

Mode	Empirical	Theoretical	Simulated
APM	25,000 (Shen, Zhao, & Huang, 1995)	24,120	28,000
PRT	*	4,800	4,800

*There is not enough PRT empirical capacity data

To calculate the theoretical capacity of each mode the below equation was used.

$$Capacity\ \left(\frac{Passengers}{Hour}\right) = \frac{Vehicle\ Capacity(\frac{Passengers}{Vehicle})}{Headway\,\frac{Seconds}{Vehicle}} * 3600\,\frac{Seconds}{Hour}$$

The simulated capacity was estimated by modeling two stations one mile apart. The APM simulated capacity was above the theoretical capacity since the effective headway (the headway that allows for perfect spacing between vehicles) was below the 120 second headway used in the theoretical calculation. PRT had its system capacity near or equivalent to the theoretical capacity, but APM's theoretical capacity is less than the empirical capacity and the theoretical capacity exceeds the empirical capacity. The simulated scenarios represent perfect operations, but transit systems rarely (and almost never) operate with perfect conditions. The empirical capacity was below the theoretical capacity because the empirical study's APM system used a headway below two minutes. A possible area of study is how sub-optimal operating conditions affect each of the automated guideway transit types' operation. Also, each of the simulators could have typical operational issues built in to adjust the capacity to more practical levels.

7.4 Sensitivity of Travel Time to Demand

The graph matrices in Chapter 5 show trip time in comparison to demand. In Figures 7.4.1 and 7.4.2, the effect of changing demand on travel and trip time is shown for PRT and APM. A loop with 5 stations at 0.5 miles apart was used for this section.

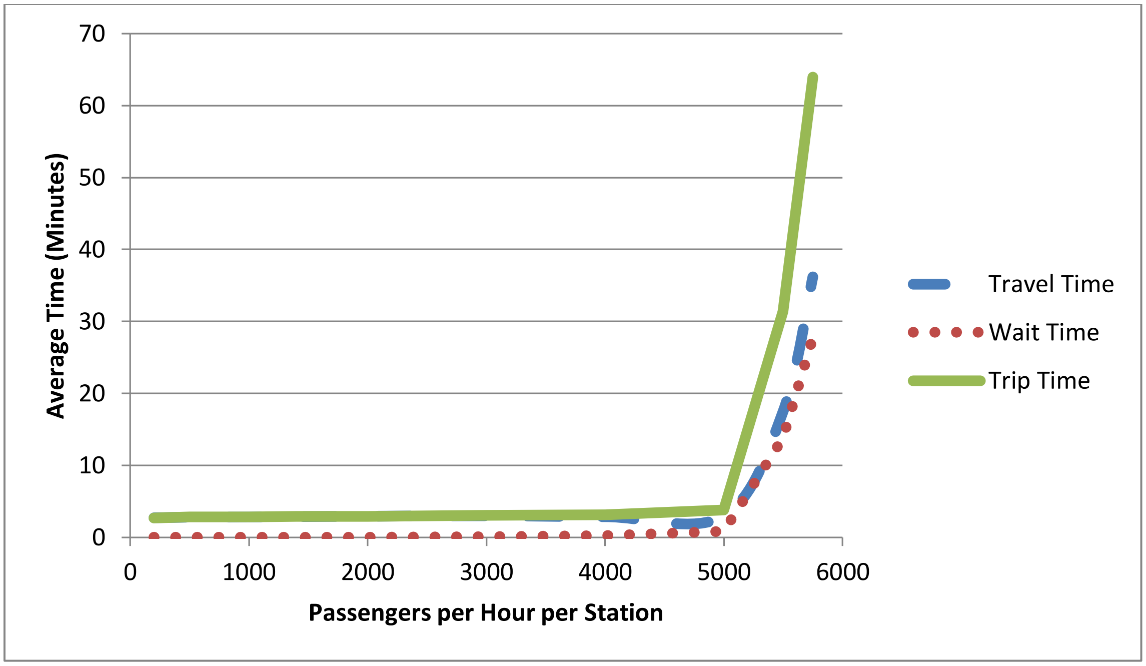


Figure 7.4.1 PRT Time Sensitivity to Demand

From about 0 to 4500 passengers per hour per station, the average trip time slowly increased for PRT solely due to travel time. After about 4500 passengers per hour per station, the wait time began to increase. Beyond 5000 passengers per hour per station, both wait time and trip time increased dramatically, though travel time was still the larger component of average trip time.

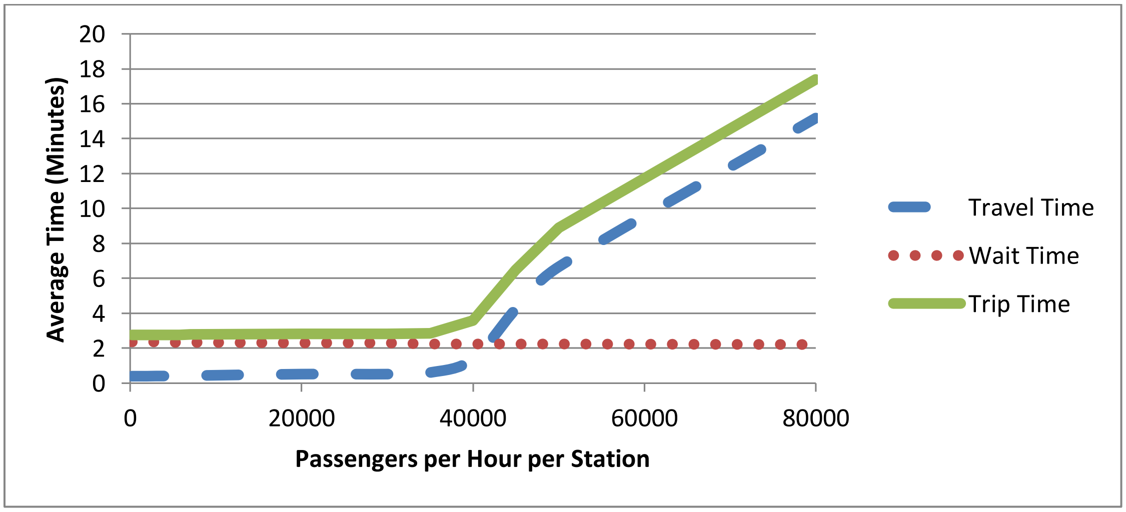


Figure7.4.2 APM Time Sensitivity to Demand

The average travel time and wait time started around 0.4 and 2.36 minutes respectively for APM. As the demand increased, the wait time slightly decreased and the travel time slightly increased due to more passengers arriving when a vehicle was dwelled at a station. The trip time was not affected. The capacity of the system was exceeded when the demand was about 35,000 per hour per station. After the capacity was exceeded, passengers had to wait through multiple train arrivals to get in a train, but the passengers’ travel time did not change. The wait time eventually increased steeply with additional passengers as the system approached capacity.

Chapter 8: Conclusions

This thesis compared the operation of two public transportation modes, namely automated people movers (APM) and personal rapid transit (PRT). APM had large capacities and could move faster across long distances, but they stopped and dwelled for long periods of time at intermediate stations. PRT took passengers directly from their origin to their destination while bypassing all intermediate stations, but could not reach high speeds and its capacity could be exceeded in situations where APM had ample capacity. Based on the simulation results, APMs and its superior speed and capacity are better suited in applications where many passengers have similar origins and destinations spaced far apart. PRTs should be built in places where passengers' origins and destinations are highly dispersed since PRT's direct and nonstop transportation to destinations eliminates the need for a passenger to wait for other passengers with different trip itineraries.

PRT performed favorably on many occasions despite the bias against PRT built in the methodology. Many of the scenarios in this thesis were conducive to APM since the scenarios featured simple geometries with demand concentrated at relatively few stations. These scenarios were not favorable to PRT since the geometry limited the network redundancy and capacity, but they could still be modeled as PRT. If there were scenarios with dispersed demand across a dense network of stations and guideway, PRT would be the faster mode, but this type of network was infeasible to model for APM since it would require an unrealistic number of routes.

Globally, APM has been the dominant mode chosen for automated guideway transit, with many projects under construction or in planning stages, but there are currently only a few PRT systems under construction or in the planning stages, and none of them are in the United States. PRT could operate with enough capacity in a variety of settings from lightly used downtown circulators to complex networks in busy urban areas; it all depends on its configuration. The dense Ithaca network could handle passenger flows at even the busiest time of the day, but a simple linear network would fail in a very crowded central business district such as Midtown Manhattan. The application should allow for a highly redundant and dense PRT network that spreads passenger demand. PRTs could work in situations with simple geometries where APMs are traditionally used, but with high demand, PRTs will not have enough capacity. If the stations are too far apart, the slow speed of PRT becomes too disadvantageous. If the stations are too close together and the demand is high, there is insufficient space for all the PRT vehicles. Many of these performance problems have been demonstrated in the tables of Chapter 5. Practitioners who are considering the full spectrum of automated guideway transit or any kind of medium/high capacity transit can use the results of this thesis as a quick reference on which mode they should consider in deeper analyses. This thesis shows that the full spectrum of automated guideway transit should be examined, rather than limiting the analysis to APM.

The subject area of this thesis could benefit from considerable further research. Group rapid transit (GRT) is an intermediate type of automated guideway transit with characteristics of both PRT and APM. It is worth determining in which types of settings GRT should operate, as opposed to PRT or APM. The only GRT in existence, the Morgantown GRT, has several operational rules that dictate how long passengers must wait for a vehicle (Kangas & Bates, 1998). In addition, GRT vehicles can be programed to serve a limited groups of stations. Another topic of research would be to evaluate what type of settings (geometry & demand) should be combined with which type of operation rules. These questions deserve considerable further research.

Appendix 1: Sample APMSM Code

```
int stations=20;
        int quarters=8;
        int Stationdemand=500;
        Supernetwork Straight = new Supernetwork ( "Straight" );
        Straight.setWrite(false);
        Straight.getNetworkpassenger().setAlternatethreshold(60);
        Straight.getNetworktrain().setCollision(false);
        Station[] Stations=new Station[stations];
        for (int i=0; i<=Stations.length-1; i++){
                Stations[i]=new Station (""+ i,i*402*quarters,0);
                Straight.getNetworkgraph().addStation(Stations[i]);
        }
        Depot depot = new Depot ( "Depot", 402*(Stations.length+1), 0);
        for (int i=0; i<=Stations.length-2; i++){
                Straight.getNetworkgraph().twowayconnectStations(Stations[i], Stations[i+1]);
        }
        Straight.getNetworkgraph().setDepot(depot,Stations[Stations.length-1]);
        Route route = new Route(Straight,2);
        for (int i=0; i<=Stations.length-2; i++){
                route.addStation(Stations[i]);
        }
        route.switchDirection();
        for(int i=Stations.length-1; i>=1; i--){
                route.addStation(Stations[i]);
        }
        route.setHeadway(120);
        Straight.getNetworktrain().setTime(3600*1, 1);
        Straight.getNetworktrain().setAcceleration(1);
        Straight.getNetworktrain().setBreakrate(1);
        Straight.getNetworktrain().setDwelltime(35);
        Straight.getNetworktrain().setCapacity(804);
        Straight.getNetworktrain().setDiffusionrate(36);
        Straight.getNetworktrain().setMaxspeed(27.77);
        Straight.getNetworkpassenger().initalize();
        for(int i=0; i<=Stations.length-1; i++){
                for(int j=0; j<=Stations.length-1; j++){
                        if(i!=j){

    Straight.getNetworkpassenger().setDemand(Stationdemand/(Stations.length-1),
                                                        Stations[i], Stations[j]);
                        }
                }
        }
```

```
//	Straight.getNetworkvisual().setScale(0.2);
//	Straight.getNetworkvisual().importLocations();
//	Straight.getNetworkvisual().finishView();
	Straight.getNetworktrain().initalize();
	Straight.getNetworkpassenger().initalize2();
	Straight.getNetworktrain().run();
```

Appendix 2: Scenarios

	System Type	Station Spacing (mi)	Station Spacing (m)	Number of Stations per route	Demand	Variation	Wait time	Theoretical	Travel Time	Trip Time	Wait time	Travel Time	Trip Time	exceeds 35%
1	Straight	0.25	402.335	5	200	No	0.42	1.00	2.80	3.22	0.00	1.59	1.59	
2	Straight	0.25	402.335	5	500	No	0.42	1.00	2.80	3.22	0.00	1.59	1.59	
3	Straight	0.25	402.335	5	1000	No	0.42	1.00	2.80	3.22	0.00	1.71	1.71	
4	Straight	0.25	402.335	5	1400	No	0.42	1.00	2.80	3.22	0.00	1.76	1.76	
5	Straight	0.25	402.335	10	200	No	0.45	1.00	4.77	5.22	0.00	2.58	2.58	
6	Straight	0.25	402.335	10	500	No	0.45	1.00	4.77	5.22	0.00	2.65	2.65	
7	Straight	0.25	402.335	10	1000	No	0.45	1.00	4.77	5.22	0.00	2.76	2.76	yes
8	Straight	0.25	402.335	10	1400	No	0.45	1.00	4.77	5.22	0.00	3.05	3.05	yes
9	Straight	0.25	402.335	20	200	No	0.47	1.00	8.89	9.36	0.03	4.73	4.76	yes
10	Straight	0.25	402.335	20	500	No	0.47	1.00	8.89	9.36	2.47	18.51	20.98	yes
11	Straight	0.25	402.335	20	1000	No	0.47	1.00	8.89	9.36	skip	skip	skip	skip
12	Straight	0.25	402.335	20	1400	No	0.47	1.00	8.89	9.36	skip	skip	skip	skip
13	Straight	0.5	804.67	5	200	No	0.45	1.00	3.46	3.91	0.00	2.47	2.47	
14	Straight	0.5	804.67	5	500	No	0.45	1.00	3.46	3.91	0.00	2.54	2.54	
15	Straight	0.5	804.67	5	1000	No	0.45	1.00	3.46	3.91	0.00	2.55	2.55	
16	Straight	0.5	804.67	5	1400	No	0.46	1.00	3.46	3.92	0.00	2.64	2.64	
17	Straight	0.5	804.67	10	200	No	0.50	1.00	5.86	6.36	0.00	4.19	4.19	
18	Straight	0.5	804.67	10	500	No	0.50	1.00	5.86	6.36	0.00	4.30	4.30	yes
19	Straight	0.5	804.67	10	1000	No	0.50	1.00	5.86	6.36	0.00	4.35	4.35	yes
2	Straight	0.5	804.67	10	1400	No	0.51	1.00	5.86	6.37	0.00	4.52	4.52	yes

0														
21	Straight	0.5	804.67	20	200	No	0.47	1.00	10.90	11.37	0.13	7.80	7.93	yes
22	Straight	0.5	804.67	20	500	No	0.47	1.00	10.90	11.37	2.58	18.73	21.31	yes
23	Straight	0.5	804.67	20	1000	No	0.47	1.00	10.90	11.37	8.06	26.00	34.06	yes
24	Straight	0.5	804.67	20	1400	No	0.47	1.00	10.90	11.37	17.57	34.19	51.76	yes
25	Straight	1	1609.34	5	200	No	0.46	1.00	4.58	5.04	0.00	4.45	4.45	
26	Straight	1	1609.34	5	500	No	0.46	1.00	4.58	5.04	0.00	4.51	4.51	
27	Straight	1	1609.34	5	1000	No	0.46	1.00	4.58	5.04	0.00	4.52	4.52	
28	Straight	1	1609.34	5	1400	No	0.46	1.00	4.57	5.03	0.00	4.55	4.56	
29	Straight	1	1609.34	10	200	No	0.47	1.00	7.72	8.19	0.03	7.54	7.57	
30	Straight	1	1609.34	10	500	No	0.47	1.00	7.72	8.19	0.00	7.61	7.61	
31	Straight	1	1609.34	10	1000	No	0.47	1.00	7.72	8.19	0.07	7.64	7.71	yes
32	Straight	1	1609.34	10	1400	No	0.47	1.00	7.72	8.19	0.15	7.81	7.96	yes
33	Straight	1	1609.34	20	200	No	0.63	1.00	14.33	14.96	0.63	14.12	14.75	yes
34	Straight	1	1609.34	20	500	No	0.63	1.00	14.33	14.96	2.63	19.94	22.57	yes
35	Straight	1	1609.34	20	1000	No	0.63	1.00	14.33	14.96	7.84	26.71	34.55	yes
36	Straight	1	1609.34	20	1400	No	0.63	1.00	14.33	14.96	15.08	35.19	50.27	yes
37	Straight	1	1609.34	5	200	Yes	0.42	1.00	6.66	7.08	0.07	6.52	6.59	
38	Straight	1	1609.34	5	500	Yes	0.42	1.00	6.66	7.08	0.21	6.55	6.58	
39	Straight	1	1609.34	5	1000	Yes	0.42	1.00	6.67	7.09	1.44	6.68	8.12	

40	Straight	1	1609.34	5	1400	Yes	0.43	1.00	6.68	7.11	1.75	6.90	8.65	yes
41	Straight	1	1609.34	10	200	Yes	0.47	1.00	10.49	10.96	0.63	10.13	10.76	
42	Straight	1	1609.34	10	500	Yes	0.47	1.00	10.49	10.96	1.03	10.20	11.23	
43	Straight	1	1609.34	10	1000	Yes	0.47	1.00	10.50	10.97	3.15	18.64	21.79	yes
44	Straight	1	1609.34	10	1400	Yes	0.47	1.00	10.50	10.97	6.16	30.44	36.60	yes
45	Straight	1	1609.34	20	200	Yes	0.48	1.00	19.82	20.30	3.04	20.18	23.22	
46	Straight	1	1609.34	20	500	Yes	0.48	1.00	19.78	20.26	4.66	33.14	37.80	yes
47	Straight	1	1609.34	20	1000	Yes	0.48	1.00	19.78	20.26	8.34	45.81	54.15	yes
48	Straight	1	1609.34	20	1400	Yes	0.48	1.00	19.77	20.25	12.24	46.86	59.10	yes
49	Straight	2	3218.68	5	200	No	0.47	1.00	6.84	7.31	0.00	8.00	8.00	
50	Straight	2	3218.68	5	500	No	0.47	1.00	6.84	7.31	0.00	8.05	8.05	
51	Straight	2	3218.68	5	1000	No	0.47	1.00	6.84	7.31	0.00	8.06	8.06	
52	Straight	2	3218.68	5	1400	No	0.47	1.00	6.83	7.30	0.06	8.05	8.11	
53	Straight	2	3218.68	10	200	No	0.81	1.00	11.51	12.32	0.32	14.28	14.60	
54	Straight	2	3218.68	10	500	No	0.81	1.00	11.51	12.32	0.28	14.30	14.57	
55	Straight	2	3218.68	10	1000	No	0.81	1.00	11.51	12.32	1.10	14.32	15.42	yes
56	Straight	2	3218.68	10	1400	No	0.81	1.00	11.51	12.32	2.22	14.41	16.63	yes
57	Straight	2	3218.68	20	200	No	3.12	1.00	21.32	24.44	3.44	26.71	30.15	yes
58	Straight	2	3218.68	20	500	No	3.13	1.00	21.32	24.45	3.52	26.98	30.49	yes
5	Straight	2	3218.68	20	1000	No	3.31	1.00	21.32	24.63	9.60	31.73	41.33	yes

9														
60	Straight	2	3218.68	20	1400	No	3.47	1.00	21.32	24.79	18.40	39.92	58.32	yes
61	Y	0.25	402.335	5	200	No	0.78	2.00	2.10	2.88	0.00	1.24	1.24	
62	Y	0.25	402.335	5	500	No	0.78	2.00	2.10	2.88	0.00	1.32	1.32	
63	Y	0.25	402.335	5	1000	No	0.78	2.00	2.10	2.88	0.00	1.37	1.37	
64	Y	0.25	402.335	5	1400	No	0.78	2.00	2.10	2.88	0.00	1.48	1.48	
65	Y	0.25	402.335	10	200	No	1.07	1.98	3.26	4.33	0.01	1.83	1.84	
66	Y	0.25	402.335	10	500	No	1.07	1.98	3.26	4.33	0.02	1.89	1.91	
67	Y	0.25	402.335	10	1000	No	1.08	1.98	3.26	4.34	0.01	1.96	1.97	
68	Y	0.25	402.335	10	1400	No	1.08	1.98	3.26	4.34	0.01	4.06	4.07	yes
69	Y	0.25	402.335	20	200	No	1.22	1.97	5.66	6.88	0.03	3.06	3.09	
70	Y	0.25	402.335	20	500	No	1.23	1.97	5.65	6.88	0.12	10.64	10.76	yes
71	Y	0.25	402.335	20	1000	No	1.23	1.97	5.65	6.88	1.10	17.80	18.90	yes
72	Y	0.25	402.335	20	1400	No	1.23	1.97	5.65	6.88	5.75	21.82	27.57	yes
73	Y	0.5	804.67	5	200	No	1.05	2	2.56	3.61	0.00	1.77	1.77	
74	Y	0.5	804.67	5	500	No	1.05	2	2.56	3.61	0.00	1.93	1.93	
75	Y	0.5	804.67	5	1000	No	1.06	2	2.56	3.62	0.00	1.95	1.95	
76	Y	0.5	804.67	5	1400	No	1.06	2	2.56	3.62	0.00	2.04	2.04	
77	Y	0.5	804.67	10	200	No	1.05	1.98	4.01	5.06	0.01	2.86	2.87	
78	Y	0.5	804.67	10	500	No	1.05	1.98	4.01	5.06	0.01	2.92	2.93	

79	Y	0.5	804.67	10	1000	No	1.05	1.98	4	5.05	0.01	2.98	2.99	
80	Y	0.5	804.67	10	1400	No	1.05	1.98	4	5.05	0.01	3.63	3.64	
81	Y	0.5	804.67	20	200	No	1.2	1.97	6.94	8.14	0.06	4.95	5.01	
82	Y	0.5	804.67	20	500	No	1.2	1.97	6.93	8.13	0.13	11.95	12.08	yes
83	Y	0.5	804.67	20	1000	No	1.2	1.97	6.93	8.13	1.23	18.53	19.76	yes
84	Y	0.5	804.67	20	1400	No	1.21	1.97	6.93	8.14	6.02	22.24	28.26	yes
85	Y	1	1609.34	5	200	No	0.87	2	3.37	4.24	0.00	3.06	3.06	
86	Y	1	1609.34	5	500	No	0.87	2	3.37	4.24	0.00	3.09	3.09	
87	Y	1	1609.34	5	1000	No	0.87	2	3.36	4.23	0.00	3.18	3.18	
88	Y	1	1609.34	5	1400	No	0.88	2	3.36	4.24	0.00	3.25	3.25	
89	Y	1	1609.34	10	200	No	1.17	1.98	5.28	6.45	0.04	5.00	5.04	
90	Y	1	1609.34	10	500	No	1.17	1.98	5.28	6.45	0.01	5.07	5.08	
91	Y	1	1609.34	10	1000	No	1.17	1.98	5.28	6.45	0.00	5.09	5.09	
92	Y	1	1609.34	10	1400	No	1.18	1.98	5.28	6.46	0.04	5.19	5.23	
93	Y	1	1609.34	20	200	No	1.32	1.97	9.13	10.45	0.28	8.91	9.19	
94	Y	1	1609.34	20	500	No	1.33	1.97	9.13	10.46	0.15	14.15	14.30	yes
95	Y	1	1609.34	20	1000	No	1.33	1.97	9.12	10.45	1.15	19.77	20.92	yes
96	Y	1	1609.34	20	1400	No	1.33	1.97	9.11	10.44	5.32	23.75	29.07	yes
97	Y	1	1609.34	5	200	Yes	1.11	2.00	3.8	4.91	0.003333	4.60	4.60	
9	Y	1	1609.34	5	500	Yes	1.11	2.00	3.8	4.91	0.89	4.60	5.49	

8														
99	Y	1	1609.34	5	1000	Yes	1.12	2.00	3.79	4.91	1.943333	4.78	6.72	
100	Y	1	1609.34	5	1400	Yes	1.12	2.00	3.79	4.91	1.951667	11.28	13.23	yes
101	Y	1	1609.34	10	200	Yes	1.11	1.95	6.43	7.54	0.20	7.20	7.40	
102	Y	1	1609.34	10	500	Yes	1.12	1.95	6.44	7.56	0.44	7.31	7.75	
103	Y	1	1609.34	10	1000	Yes	1.12	1.95	6.44	7.56	2.41	24.74	27.15	yes
104	Y	1	1609.34	10	1400	Yes	1.13	1.95	6.44	7.57	4.11	36.05	40.16	yes
105	Y	1	1609.34	20	200	Yes	1.34	1.92	11.9	13.24	1.34	16.58	17.92	
106	Y	1	1609.34	20	500	Yes	1.34	1.92	11.95	13.29	1.25	36.18	37.43	yes
107	Y	1	1609.34	20	1000	Yes	1.34	1.92	11.92	13.26	5.44	47.39	52.83	yes
108	Y	1	1609.34	20	1400	Yes	1.36	1.92	11.93	13.29	13.75	51.47	65.22	yes
109	Y	2	3218.68	5	200	No	0.99	2	4.99	5.98	0.00	5.37	5.37	
110	Y	2	3218.68	5	500	No	0.99	2	4.99	5.98	0.00	5.42	5.42	
111	Y	2	3218.68	5	1000	No	1	2	4.99	5.99	0.00	5.47	5.47	

112	Y	2	3218.68	5	1400	No	1.01	2	4.98	5.99	0.08	5.50	5.58	
113	Y	2	3218.68	10	200	No	1.33	1.98	7.85	9.18	0.17	9.12	9.29	
114	Y	2	3218.68	10	500	No	1.33	1.98	7.85	9.18	0.01	9.16	9.17	
115	Y	2	3218.68	10	1000	No	1.34	1.98	7.84	9.18	0.35	9.18	9.53	
116	Y	2	3218.68	10	1400	No	1.35	1.98	7.84	9.19	0.96	9.28	10.24	
117	Y	2	3218.68	20	200	No	1.39	1.97	13.55	14.94	1.33	16.64	17.97	
118	Y	2	3218.68	20	500	No	1.39	1.97	13.53	14.92	0.97	19.32	20.29	yes
119	Y	2	3218.68	20	1000	No	1.4	1.97	13.53	14.93	2.74	22.65	25.39	yes
120	Y	2	3218.68	20	1400	No	1.4	1.97	13.52	14.92	7.85	26.56	34.41	yes
121	Loop	0.25	402.335	5	200	No	0.38	0.92	1.99	2.37	0.00	1.84	1.84	
122	Loop	0.25	402.335	5	500	No	0.38	0.92	1.99	2.37	0.00	1.94	1.94	
123	Loop	0.25	402.335	5	1000	No	0.38	0.92	1.99	2.37	0.00	1.95	1.95	
124	Loop	0.25	402.335	5	1400	No	0.38	0.92	1.99	2.37	0.00	1.99	1.99	

125	Loop	0.25	402.335	10	200	No	0.37	0.94	3.49	3.86	0.00	2.80	2.80	
126	Loop	0.25	402.335	10	500	No	0.37	0.94	3.49	3.86	0.00	2.91	2.91	
127	Loop	0.25	402.335	10	1000	No	0.37	0.94	3.49	3.86	0.00	2.95	2.95	
128	Loop	0.25	402.335	10	1400	No	0.37	0.94	3.49	3.86	0.00	2.99	3.00	
129	Loop	0.25	402.335	20	200	No	0.48	0.925	6.74	7.22	0.011667	4.693333333	4.71	
130	Loop	0.25	402.335	20	500	No	0.48	0.925	6.74	7.22	0.001667	4.9	4.90	
131	Loop	0.25	402.335	20	1000	No	0.48	0.925	6.74	7.22	1.173333	10.51	11.68	yes
132	Loop	0.25	402.335	20	1400	No	0.48	0.925	6.74	7.22	2.40	12.71	15.11	yes
133	Loop	0.5	804.67	5	200	No	0.4	0.92	2.36	2.76	0.00	2.71	2.71	
134	Loop	0.5	804.67	5	500	No	0.4	0.92	2.36	2.76	0.00	2.80	2.80	
135	Loop	0.5	804.67	5	1000	No	0.4	0.92	2.36	2.76	0.00	2.82	2.82	
136	Loop	0.5	804.67	5	1400	No	0.4	0.92	2.36	2.76	0.00	2.88	2.88	
137	Loop	0.5	804.67	10	200	No	0.42	0.94	4.28	4.7	0.00	4.27	4.28	

138	Loop	0.5	804.67	10	500	No	0.42	0.94	4.28	4.7	0.00	4.33	4.33	
139	Loop	0.5	804.67	10	1000	No	0.42	0.94	4.28	4.7	0.00	4.36	4.36	
140	Loop	0.5	804.67	10	1400	No	0.42	0.94	4.28	4.7	0.00	4.41	4.41	
141	Loop	0.5	804.67	20	200	No	0.48	0.925	8.16	8.64	0.04	7.19	7.24	
142	Loop	0.5	804.67	20	500	No	0.48	0.925	8.15	8.63	0.01	7.37	7.39	
143	Loop	0.5	804.67	20	1000	No	0.48	0.925	8.15	8.63	1.23	10.72	11.96	yes
144	Loop	0.5	804.67	20	1400	No	0.48	0.925	8.15	8.63	2.41	12.74	15.15	yes
145	Loop	1	1609.34	5	200	No	0.36	0.92	3.22	3.58	0	4.39	4.39	
146	Loop	1	1609.34	5	500	No	0.36	0.92	3.22	3.58	0.00	4.45	4.45	
147	Loop	1	1609.34	5	1000	No	0.36	0.92	3.22	3.58	0.00	4.47	4.47	
148	Loop	1	1609.34	5	1400	No	0.36	0.92	3.22	3.58	0.00	4.51	4.51	
149	Loop	1	1609.34	10	200	No	0.41	0.94	5.81	6.22	0.02	7.07	7.10	
150	Loop	1	1609.34	10	500	No	0.41	0.94	5.81	6.22	0.00	7.15	7.15	

151	Loop	1	1609.34	10	1000	No	0.41	0.94	5.81	6.22	0.00	7.13	7.13	
152	Loop	1	1609.34	10	1400	No	0.41	0.94	5.81	6.22	0.02	7.15	7.17	
153	Loop	1	1609.34	20	200	No	0.49	0.925	10.95	11.44	0.52	12.33	12.85	
154	Loop	1	1609.34	20	500	No	0.49	0.925	10.95	11.44	0.62	12.42	13.03	yes
155	Loop	1	1609.34	20	1000	No	0.49	0.925	10.95	11.44	1.85	12.55	14.40	yes
156	Loop	1	1609.34	20	1400	No	0.49	0.925	10.95	11.44	2.48	13.30	15.78	yes
157	Loop	2	3218.68	5	200	No	0.48	0.92	4.98	5.46	0.00	7.71	7.71	
158	Loop	2	3218.68	5	500	No	0.48	0.92	4.98	5.46	0.00	7.71	7.71	
159	Loop	2	3218.68	5	1000	No	0.48	0.92	4.98	5.46	0.00	7.75	7.75	
160	Loop	2	3218.68	5	1400	No	0.48	0.92	4.98	5.46	0.01	7.76	7.78	
161	Loop	2	3218.68	10	200	No	0.46	0.94	8.78	9.24	0.40	12.61	13.01	
162	Loop	2	3218.68	10	500	No	0.46	0.94	8.78	9.24	0.12	12.62	12.74	
163	Loop	2	3218.68	10	1000	No	0.46	0.94	8.78	9.24	0.90	12.61	13.51	

164	Loop	2	3218.68	10	1400	No	0.46	0.94	8.78	9.24	1.01	12.63	13.63	
165	Loop	2	3218.68	20	200	No	0.5	0.925	16.28	16.78	3.42	22.40	25.82	
166	Loop	2	3218.68	20	500	No	0.5	0.925	16.28	16.78	3.40	22.42	25.82	
167	Loop	2	3218.68	20	1000	No	0.5	0.925	16.28	16.78	5.03	22.47	27.50	
168	Loop	2	3218.68	20	1400	No	0.5	0.925	16.28	16.78	6.35	22.63	28.98	yes
169	Loop with Legs	0.25	402.335	10	200	No	0.47	1	4.38	4.85	0.03	2.93	2.96	
170	Loop with Legs	0.25	402.335	10	500	No	0.47	1	4.38	4.85	0.05	2.99	3.04	
171	Loop with Legs	0.25	402.335	10	1000	No	0.47	1	4.38	4.85	0.03	3.02	3.05	
172	Loop with Legs	0.25	402.335	10	1400	No	0.47	1	4.38	4.85	0.02	3.04	3.06	
173	Loop with Legs	0.25	402.335	20	200	No	0.47	1	7.55	8.02	0.12	3.99	4.11	
174	Loop with Legs	0.25	402.335	20	500	No	0.47	1	7.55	8.02	0.11	4.26	4.37	yes
175	Loop with Legs	0.25	402.335	20	1000	No	0.47	1	7.55	8.02	1.00	14.61	15.61	yes
176	Loop with Legs	0.25	402.335	20	1400	No	0.47	1	7.55	8.02	2.72	17.38	20.10	

177	Loop with Legs	0.5	804.67	10	200	No	0.46	1	5.62	6.08	0.07	4.54	4.61	
178	Loop with Legs	0.5	804.67	10	500	No	0.46	1	5.62	6.08	0.05	4.62	4.67	
179	Loop with Legs	0.5	804.67	10	1000	No	0.46	1	5.62	6.08	0.02	4.62	4.64	
180	Loop with Legs	0.5	804.67	10	1400	No	0.46	1	5.62	6.08	0.02	4.66	4.68	
181	Loop with Legs	0.5	804.67	20	200	No	0.49	1	9.44	9.93	0.30	6.51	6.81	
182	Loop with Legs	0.5	804.67	20	500	No	0.49	1	9.44	9.93	0.11	6.72	6.83	yes
183	Loop with Legs	0.5	804.67	20	1000	No	0.49	1	9.44	9.93	1.12	15.08	16.20	yes
184	Loop with Legs	0.5	804.67	20	1400	No	0.49	1	9.44	9.93	2.66	18.07	20.73	yes
185	Loop with Legs	1	1609.34	10	200	No	0.47	1	8.06	8.53	0.18	7.73	7.91	
186	Loop with Legs	1	1609.34	10	500	No	0.47	1	8.05	8.52	0.04	7.77	7.81	
187	Loop with Legs	1	1609.34	10	1000	No	0.47	1	8.05	8.52	0.13	7.79	7.92	
188	Loop with Legs	1	1609.34	10	1400	No	0.47	1	8.05	8.52	0.44	7.81	8.25	
189	Loop with Legs	1	1609.34	20	200	No	0.48	1	12.99	13.47	0.81	11.37	12.18	

190	Loop with Legs	1	1609.34	20	500	No	0.48	1	12.99	13.47	0.51	11.56	12.07	yes
191	Loop with Legs	1	1609.34	20	1000	No	0.48	1	12.99	13.47	1.51	16.45	17.96	yes
192	Loop with Legs	1	1609.34	20	1400	No	0.48	1	12.99	13.47	3.28	20.50	23.78	yes
193	Loop with Legs	1	1609.34	10	200	Yes	0.43	1	7.79	8.22	0.29	7.18	7.47	
194	Loop with Legs	1	1609.34	10	500	Yes	0.43	1	7.78	8.21	0.55	7.22	7.77	
195	Loop with Legs	1	1609.34	10	1000	Yes	0.43	1	7.78	8.21	1.55	7.30	8.85	
196	Loop with Legs	1	1609.34	10	1400	Yes	0.43	1	7.78	8.21	2.45	8.42	10.87	yes
197	Loop with Legs	1	1609.34	20	200	Yes	0.49	1	13.37	13.86	1.28	11.59	12.87	
198	Loop with Legs	1	1609.34	20	500	Yes	0.49	1	13.34	13.83	2.19	12.02	14.21	yes
199	Loop with Legs	1	1609.34	20	1000	Yes	0.49	1	13.31	13.8	2.98	28.97	31.95	yes
200	Loop with Legs	1	1609.34	20	1400	Yes	0.49	1	13.33	13.82	3.71	36.87	40.58	yes
201	Loop with Legs	2	3218.68	10	200	No	0.48	1	12.99	13.47	0.64	13.98	14.62	
202	Loop with Legs	2	3218.68	10	500	No	0.48	1	12.99	13.47	0.31	13.99	14.30	

203	Loop with Legs	2	3218.68	10	1000	No	0.48	1	12.99	13.47	1.39	14.00	15.39	
204	Loop with Legs	2	3218.68	10	1400	No	0.48	1	12.99	13.47	2.278333	14.03	16.31	
205	Loop with Legs	2	3218.68	20	200	No	0.5	1	19.94	20.44	1.86	20.99	22.85	
206	Loop with Legs	2	3218.68	20	500	No	0.5	1	19.95	20.45	1.583333	21.06	22.64	
207	Loop with Legs	2	3218.68	20	1000	No	0.5	1	19.95	20.45	3.13	21.91	25.04	yes
208	Loop with Legs	2	3218.68	20	1400	No	0.5	1	19.95	20.45	6.87	25.87	32.74	yes

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