Technical Specifications
for ITNS Technology
(Intelligent Transportation Network System)

August 2017

Contents

1. System Specifications

Introduction

Many of the specifications discussed in this document cannot be based on agreed standards, because none exist. These specifications must be based on agreements between the client and the supplier. The specifications given are recommendations of the supplier, but require agreement or modification by the client.

1.1 Emergency Evacuation

1.1.1 By using dual thrusters, fault-tolerant dual duplex control system, back-up traction power and conservatively designed sealed bearings, a vehicle will rarely become so disabled that it cannot be pushed into a station where the passengers can disembark in safety. It has been estimated that in a fleet of 500 vehicles, one vehicle may have to be pushed no more often than once in 150 years.[1] In the unlikely event that a vehicle becomes disabled, the system shall be designed to allow the following vehicle to push the disabled vehicle to the next station under direction of Central Control.

1.1.2 If a disabled vehicle cannot be pushed, a cherry-picker can provide an acceptable alternative. A cherry picker with a garaging facility may be purchased for the local fire department as part of system implementation. Fault-tree and FMEA analysis has been used to determine the probability of occurrence of events that require passenger rescue.

1.1.3 In the extremely rare event of a collision between vehicles, it may be impossible or inadvisable to move the vehicles under either automatic control or remote manual control from Central Control. Voice communication between Central Control and the vehicle will help establish this.

1.1.4 The vehicle cabin shall be constructed of fire-retardant materials and will be separated from the primary electrical and propulsion systems. The cabin floor will contain a fire-resistant barrier to any fire started in the 600-volt propulsion equipment in the chassis. A minimum of electrical equipment shall be in the cabin, and it shall be limited to low-voltage components.

1.1.5 Smoke and temperature detectors in the cabin and the electrical compartments shall notify Central Control automatically and direct the vehicle to the next station. The next station shall be reachable in less than

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[1] J. E. Anderson, “Failure Modes and Effects Analysis and Minimum Headway in PRT Systems.”

one minute and offers the safest egress for passengers, often before they would become aware of the potential of a fire. People on the station platform shall be warned of the approaching vehicle and the damaged vehicle will be moved out of the station as soon as the passengers egress. Cabin ventilation shall be provided.

1.2. Stations Attached to or Within Buildings

Issue: NFPA-130 has required that stations be separated from buildings by a fire-hardened barrier with a three-hour fire rating.
Recommendation: The three-hour NAPA-130 standard should not be applied. This requirement is too conservative, precludes creative integration of stations with other building facilities and increases costs unnecessarily.

1.3 Passenger Restraints

The perceived similarity between the passenger compartments of PRT vehicles and automobiles suggests that laws governing seat belts and infant/toddler seats may apply. Padded interior surfaces and shock-absorbing bumpers should be provided and should offer reasonable protection for adults and older children. Seat belts may also be used if desired but it is best to have the safety devices out of sight. Initial decisions may be changed once safety is demonstrated through long-term operation.

It is important to note that the similarity between PRT and automobiles does not extend beyond the passenger compartment. Unlike the automobile, head-on collisions and roll-overs are not possible in PRT systems of our design. Also, the maximum normal operating speed for the initial deployment of ITNS is well below that of automobiles on interstate highways. Finally, and most importantly, the greatest cause of accidents in both automobiles and conventional public transportation systems is human error, which is eliminated in ITNS through automation.

1.3.1 Seat Belts

ITNS vehicles can be equipped with retractable seat belts, but if constraints are still desired, once the extremely low probability of a sudden stop is verified, a better alternative is an airbag that would cover the windshield. While the probability of a collision will be extremely small, seat belts provide an extra margin of safety, both actual and perceived, especially for those passengers who are uncomfortable traveling without them; however, too few people will use them. Seat belts may be added at any time with minimal effort and low cost.

1.3.2 Infant Seats

Infant seats may be installed in the form of a fold-down seat near the dashboard. This design is convenient for passengers and should not increase boarding time significantly. Fold-down seats for children can be added if desired.

1.3.2 Toddler Seat

Toddler seats may be incorporated in a similar manner to the infant seats and can be added if desired.

1.4 "Brick-wall" Stopping

"Brick-Wall" stopping is a standard requirement established by the 1911 Railway Safety Act to set the minimum allowable distance or time headway between trains. If vehicles are moving along a guideway at line speed under the "brick-wall stop" rule, the distance between each pair of adjacent vehicles must be such that if the leading vehicle comes to a stop instantaneously, the following vehicle has sufficient distance to stop before hitting the stopped vehicle without exceeding the emergency jerk and acceleration comfort limits. The "brick-wall" or instantaneous stopping criterion is conservative because, in a carefully designed PRT system, the probability of an instantaneous stop is negligible.[2]

The minimum allowable headway is important because it determines line capacity. For example, a system that operates at one-second minimum headway has five times the line capacity of a system that operates at five-second minimum headway. Close headway operation (less than two seconds) need not be required in the first public PRT systems; however, a great deal of experience with simulations shows that it will be required as the system is expanded into a larger network.

A minimum-headway policy decision will be required if headways are to be reduced below approximately two seconds. With today's technology, ITNS can be designed

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[2] Op. cit.

to operate with headways below one-half of a second, effectively providing ten times the capacity of a five-second system. (Such short-headway operation was demonstrated during the 1990s by the National Automated Highway Consortium.) The safety record of ITNS during safety testing will provide an appropriate basis upon which headway policy can be established.

ITNS shall be designed to be capable of operating at half-second headway, but operation with passengers must be delayed until certified to be safe. The criterion for safety should be based on the number of incidents per billion vehicle-miles of operation, which must be less than one.

1.5 Station-Floor to Vehicle-Floor Interface

The station floor shall be level with the vehicle floor within 6 mm. The edge of the station floor shall be no more than 12 mm from the edge of the vehicle floor.

1.6 Walking on the Guideway

People walking along the top of the guideway present a danger to themselves, vehicle passenger, and people beneath the guideway. There are several options available to deter people from walking on the guideway; however, none of them positively prevent people from doing so. A list of options follows:

- Build a slope on the top of the guideway covers to make both walking and snow accumulation difficult.
- Provide a barrier between the station platform and vehicles with doors the width of the vehicle door that only open when a vehicle is in place (as with an elevator.)
- Post notices indicating the dangers associated with walking on the guideway, and institute a large fine for doing so.
- Provide infrared sensors at the points where the vehicles enter and leave the station that trigger an alarm if a person passes but not if a vehicle passes.

Recommendation: In a cold climate, the ticket buying and loading area should be enclosed, with doors the width of the vehicle door only at the positions adjacent to the stopped vehicle doors, and with a control that permits the station door to open only when a vehicle is present. This is identical to the interface between a building lobby and an elevator.

1.7 Surveillance of Unattended Stations

A closed-circuit television (CCTV) surveillance system shall be installed in each station. Cameras mounted in the stations can be connected to monitors at Central Control. Station platforms shall be unobstructed to provide a clear view of the cameras, and the station design shall eliminate potential hiding places. Other components and characteristics of the CCTV system follow:

- CCTV coverage of all parts of the station should be provided, including stairwells, elevator doors, ticketing areas and other passenger facilities such as change machines and public telephones.
- Motion sensors will alert Central Control to the presence of more than one person in the station during off-peak or late-night hours. If a motion sensor is triggered, the appropriate camera view will be brought up on one of the Central Control monitors and a bell will ring. (Since there will be many fewer monitor screens than cameras, normal operation would consist of a rotation of camera views on Central Control monitors.)
- Emergency call buttons should be in the stations for use by passengers.
- Given an alarm or the detection of a suspicious person, Central Control may dispatch police or security personnel to the station and make announcements through the station intercom system.
- Notices in the stations should inform passengers of the security system and associated procedures. The obvious presence of CCTV cameras and the likelihood of being apprehended will discourage individuals from robbing or assaulting passengers.

1.8 Unwanted Person Entering a Vehicle with a Passenger

It is possible that after a passenger enters a vehicle but just before the door closes, a person intent on robbery or assault might enter the vehicle. The passenger would then be trapped in the vehicle with the person for the duration of the trip. Such a problem can of course occur with ordinary automobiles.

Recommendation: If a passenger calls for help from the vehicle through either a silent alarm located in the vehicle cabin or the intercom system, police can be directed to the destination station or other station (including the maintenance and control facility) to which the vehicle could be redirected. The unauthorized passenger is then readily apprehended. Notices posted in the stations would inform passengers of these security procedures, and the near certainty of being apprehended would discourage individuals from accosting passengers in vehicles.

Recommendation: In addition to an emergency intercom call button in each vehicle, there should be a silent alarm that annunciates in Central Control. The silent alarm might be activated by a colored, touch-sensitive strip along the windows, but the problem of a child activating it must be taken into account.

1.9 Emergency Door Activation

In certain rare situations, such as the cabin filling with smoke or the vehicle loosing electric power, there is a need to open the door manually. We recommend that the door should have a manual over-ride that is readily accessible to fire/life-safety personnel outside the vehicle. Passengers should also have access to a manual over-ride subject to the following limitations:

- The door should remain latched if the vehicle is not in a station.
- The latch should not be readily accessible. For example, it could be behind a breakable access panel or require a complex set of motions to activate.
- If the cabin fills with smoke when the vehicle is not in a station, means of venting must be provided; however, the doors may be opened. The smoke detector should cause the vehicle to stop at the nearest station and then cause the door to open. This action will generally occur in less than 30 seconds – too little time for smoke to cause serious injury.

1.10 Guideway Support-Pole Protection

Guideway support poles located adjacent to highways may be struck by automobiles or trucks moving at high speeds. Measures must be taken to minimize the negative consequences of such an event. The post could be designed to break away from the guideway upon impact or the base of the post could be designed to resist the impact.

Recommendation: If a guideway support post is located where it may be impacted by a high-speed vehicle, either a highway barrier should be placed around the post to deflect vehicles away or an enlarged bumper-height concrete base pad should be placed at the base of the post. It is not practical to use a breakaway post in this application because the post required to support the guideway is too robust to break away on impact.

1.11 Maximum Station Speed

The maximum speed of a vehicle in the station area shall be 8 meters per second.

1.12 Access for the Disabled

The system shall be designed to conform to the Americans with Disabilities Act of 1990. The issue is the level of disability that must be accommodated.

1.12.1 Wheel Chairs

Issue 1: Quadriplegics use voice-activated wheel chairs. Should the system (elevator, ticketing, door closure, etc.) also be voice-activated to accommodate unaccompanied quadriplegics?

Recommendation: Voice-activated systems are not well suited for public transportation systems because of the relatively large amount of random voice inputs in the station area. The design of reliable voice-activated systems would be difficult and costly, and it may not be possible to completely preclude accidental activation of the various systems. Accidental activations could interfere with system operations. Any decision should be made with awareness of these potential problems. It should not be necessary to accommodate unaccompanied quadriplegics. The cabin should be designed so that with seats folded up a wheelchair can enter and face forward following which a seat can be folded down for an attendant.

Issue 2: Means of restraining a wheelchair are used in some types of vehicles. Should PRT vehicles also provide wheelchair restraints?

Recommendation: The wheelchair's own brakes are sufficient in view of the relatively small forces acting on the wheelchair during normal system operation. In the unlikely event of a collision, the confined space in the cabin will limit wheelchair motion. Therefore, it is not necessary to provide wheelchair restraints.

Issue 3: Maximum dimensions and weight of the wheelchair?

1.12.2 Visually Impaired

Blind and visually-impaired people must be able to use the system as easily as any other public transportation system.

Recommendation: Braille plaques and pre-recorded or voice-synthesized messages should be used to provide guidance for the visually impaired. Stations should use similar layouts to maximize consistency, and the platform surface should be textured in the vehicle boarding area. As there are no intermediate stops, it is clear when to exit the vehicle.

1.12.3 Hearing Impaired

Hearing-impaired and deaf people must be able to use the system as easily as any other public transportation system.

Recommendation: Signs and visual displays should be used as required to provide guidance for the hearing impaired. The ticketing device and the vehicle should include visual display equipment that may be used for both routine and emergency messages.

1.12.4 Illiterate & Foreign Passengers

Illiterate and foreign-speaking passengers should be able to use the system as easily as any other public transportation system.

Recommendation: Visual ticketing and boarding-process information should use graphics and international symbols to the greatest extent possible. In addition, visual-display devices for ticketing and in the vehicle could permit the user to select one of several available languages. Pre-recorded or voice-synthesized messages could also be available in several user-selected languages.

1.12.5 The Elderly Person using a Walker

The vehicle entry shall be designed to make it easy for an elderly person to walk straight into the vehicle and sit down without having to worry about bumping his or her head.

1.13 Passenger Comfort and Convenience

1.13.1 Unacceptable Vehicles

The activities of a passenger may leave a vehicle in a condition that is unacceptable to subsequent passengers.

Recommendation: The stanchion located at the vehicle berth for establishing the vehicle destination should have “vehicle-reject” button. If this button is pressed, one of the following actions may be initiated by Central Control:

- The first time a vehicle is rejected, it should be sent empty to the next open station. If the vehicle is rejected a second time, it should be sent to the maintenance and cleaning facility.
- If a passenger rejects two vehicles, Central Control would communicate via the intercom with the passenger to determine the cause for the rejections. Verbal communication is desirable to preclude pranksters from rejecting numerous vehicles for amusement. The station's CCTV cameras may also be used to provide Central Control with additional information.

1.13.2 Windshield Wipers

Rain and snow on the vehicle windshield and interior fogging may obstruct the passenger's view.

Recommendation: Hot-air defrosters should be provided to clear condensation and melt snow and ice. A hydrophobic coating can be applied to the windshield's exterior surface to aid water runoff. The use of windshield wipers is not recommended because they require a hard windshield material such as glass. A glass windshield is heavy and would also be expensive given its large size and highly-contoured shape. Glass windshields are also less safe in a collision than the more flexible and fracture-resistant plastic windshields. The windshield wiper arm, blade, motor, and linkage would be high-maintenance items and would add to vehicle cost.

1.13.3 Station Access

Each elevated station not connected to the second floor of a building shall be equipped with an elevator.

1.13.4 Access to Useful Information

Recommendation: Each vehicle should be equipped with a television screen that can be tuned to system information, marketing information, travel information, or entertainment.

1.13.5 Wave-Offs

Since people arrive at stations and board at random intervals, the arrival time of vehicles at any station is also random. Each station must be designed to accommodate a certain maximum flow, but account must be taken that that flow may for a short time be exceeded. If there is no room in a station when a vehicle arrives, it must be commanded to by-pass the station, i.e., "waved off," whereupon it circles around on the shortest path and tries again to enter the station. Experience with simulations has shown that, because of statistical variations in the arrival rate, an n-berth station must have at least n+3 waiting positions to keep wave-offs to an acceptable level.

Recommendation: Determine by simulation the number of waiting positions needed to keep the number of wave-offs to any station to be no more than one occurrence in 1000 arrivals and give a prize to the passengers waved off.

1.14 Operational Convenience

1.14.1 Disabled Vehicle

If a vehicle becomes disabled, the vehicle can almost always be pushed to the next station by the vehicle behind where the passengers will exit the vehicle. The passengers in the pushing vehicle will also exit their vehicle. These passengers must be re-booked to their original destination.

Recommendations: We see two options:

- Once passengers have been discharged from disabled and pushing vehicles, they can be instructed via the stanchion intercoms to wait at their berths for the next vehicle. The next two vehicles entering the station can be automatically programmed to the passengers' original destination.
- Since this action will be extremely rare, the passengers could go to the ticketing machine and be reissued tickets, with voice communication to Central Control.

1.14.2 Communication

Communication with passengers is required. The preferred approach is threefold:

- Central Control can issue announcements to the following optional locations:
    - Whole system
    - All stations

  - All vehicles
  - A single zone
  - A single vehicle

- Two-way audio communication between Central Control and a single vehicle, a ticketing machine, and a station-berth station shall be provided. Passengers shall be able to initiate communication by pressing an intercom button.

- Visual displays in the vehicles and ticketing machines can present information as required to assist passengers with ticketing and boarding procedures.

1.15 Ticketing

1.15.1 Fare policy

Many aspects of fare policy are a function of the ticketing software and can be changed with minimal inconvenience. These are denoted by an asterisk in the following list.

1.15.1.1 Number of Passengers in one Vehicle

The cost of a trip should be per vehicle, not per passenger.

1.15.1.2 Distance*

The price of a trip should be based on the distance between origin and destination.

1.15.1.3 Time of Day*

The ticketing systems should be designed to provide a different price structure as a function of the time of day or day of the week.

1.15.2 Ticketing Process

Ticketing may be done in several ways. Various approaches can be evaluated on a system-wide basis, including the use of magnetically encoded cards and chip-based smart cards.

1.16 Environment

The design of the system will accommodate a wide range of weather and environmental conditions. The structural design, power requirements, and design aspects to address issues related to ice and snow depend on the range of weather conditions associated with normal, degraded and shut-down conditions.

1.16.1 Wind

1.16.1.1 System Operation

Performance requirements such as the operating speed, maximum continuous grade, and wind loads dictate the size of the vehicle propulsion units, power supply equipment, and numerous other system components.

Recommendation: Design for no degradation in performance in sustained winds up to 30 mph, degraded service for sustained wind speeds between 30 and 60 mph, and no service above 60 mph. Between 30 and 60 mph winds, the sum of the wind speed and the vehicle speed should be no more than 60 mph.

1.16.1.2 Maximum Wind

Certain aspects of the structural design of the vehicle, guideway, and support posts are governed by the maximum wind.

Recommendation: With no vehicles out on the guideway away from stations or storage, design for 125 mph winds with no damage to the vehicles, guideway, or appurtenant equipment.

1.16.1.3 Sharp-Edged Gusts

In downtown settings, there may be strong winds blowing down one set of streets with no wind in the cross streets.

Recommendation: Design the car suspension and control so that a vehicle suddenly encountering a gust up to 50 mph will not be uncomfortable for the passengers.

1.16.2 Ice and Snow

1.16.2.1 Freezing Precipitation

Recommendation: The system should be designed to operate throughout the range of local weather conditions, except for winds more than 60 mph. The guideway is enclosed except for a 3-in-wide slot on the top (wider at merge and diverge points), and a 6-in-wide slot at the bottom to permit precipitation or debris to exit. The power rails within the guideway have additional protection to preclude frost formation resulting from radiation to the winter-night sky. Vehicles will have hot-air defrosters to keep the windshield clear. Propulsion and braking is through linear induction motors so water and light ice on the running rails will not affect acceleration or braking rates.

1.16.2.2 Snow

Snow will accumulate on and in the guideway and on the vehicles.

Recommendation: The preferred approach to snow removal is a plow on some of the vehicles that directs snow off the main support rails down through the gap at the bottom of the guideway. A complement of vehicles running continuously during a snow storm will prevent significant accumulation. The maintenance facility will be designed to accommodate snow-covered vehicles and the hot-air defroster will keep the windshield clear.

1.16.3 Temperature Range

The system shall be designed to be operational in temperatures ranging from -45° C to +50°C.

1.16.4 Air-Bourn Pollutants

The system shall be designed for the most corrosive air conditions such as salt, acid rain, sand, etc.

1.16.5 Electromagnetic Radiation

The cabin floor shall contain an electrically conducting layer to shield the passengers from EM radiation from the chassis.

1.17 Loading

- Each vehicle shall be designed to carry a maximum load of 800 lb.
- The guideway shall be designed for fully loaded vehicles nose to tail with a 60-mph crosswind.
- The unloaded guideway shall be designed for a 125-mph crosswind.

1.18 Performance

The standard system shall be designed for a maximum speed of 35 mph and for a maximum steady grade of 6%, and with dependability[3] in excess of 99.99%. Design features shall be used to permit the system to be expanded indefinitely.

1.19 Physical Characteristics

- The normal guideway span shall be 90 ft.
- The normal elevation to the bottom of the guideway shall be 16 ft.
- The interior width, height, and leg room in the cabin is given in the cabin specification

1.20 Standards

In the Northeastern Illinois RTA PRT Design Study, the team assembled a list of over 80 specifications of various kinds that will need to be reviewed. The most important of these relate to safety, human comfort, and electromagnetic interference.

Recommendation. Whenever practical, all dimensions shall be measured in metric units.

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[3] J. E. Anderson, "Dependability as a Measure of On-Time Performance of Personal Rapid Transit Systems"

2. Program of System Safety and Reliability

A major part of any engineering program related to automated guideway transit is to ensure that the system will be safe.[4] The Automated People Mover Standards require that any APM program have on its staff at least one full-time person devoted to safety issues operating separate from the design teams. This person must be familiar with the analysis of safety problems in complex systems that include real-time, safety-critical software. Safety issues include fire safety, robustness and redundancy in the software, design loads and stresses, and all other issues involving safety. Safety was treated in some detail in two reports from the Chicago RTA PRT Design Study.[5]

A great deal of systems engineering work[6] has been done to arrive at the current configuration of ITNS. The work remaining is mainly to be sure that the hardware and the system-control protocols take advantage of the current state of the art. The safety engineering team shall

1. Review prior work on hazards analysis, fault-tree analysis, and failure-modes-and-effects analysis.
2. Tabulate data on component reliability from data sources such as www.e-reliability.com, from the AF Reliability Center at Griffiss Air Force Base, Rome, NY, and from other Internet sites. This work can be updated from the above-mentioned Chicago PRT Design Study.
3. Estimate system dependability and hence safety using available models.
4. Estimate the optimum component mean times to failure that meet the system dependability criterion at minimum life-cycle cost.[7]
5. Review the ASCE Automated People Mover Standards to be sure that they are complied with where relevant.
6. Examine in detail the safety implications of the component and subsystem design, and recommend changes when necessary.
7. Become conversant in safety technology, for example through the System Safety Society.

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[4] J. E. Anderson, “Safe Design of PRT Systems,” *J AT*, 28:1(1994):1-15.

[5] “Safety, Security & Failure Management Report” and “Fault-Tree Analysis and Reliability, Availability & Maintainability Analysis,” PRT Design Study, Chicago RTA, 1991.

[6] J. E. Anderson, *Contributions to the Development of Personal Rapid Transit*. A 1500-page book in 3 volumes.

[7] J. E. Anderson, "Life-Cycle Costs and Reliability Allocation in Automated Transit," *High Speed Ground Transportation*, 11:1(1977):1-18.

3. Final Design and Assembly of the Cabin

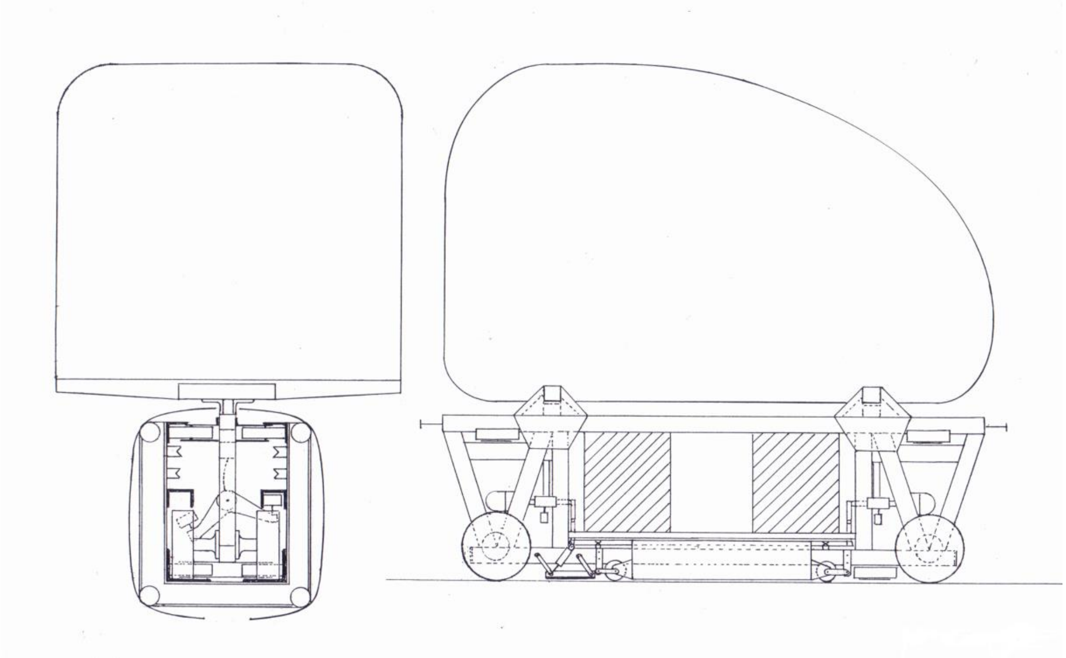

Figure 3-1. A Sketch of the ITNS Vehicle.

The specifications described here are for the work needed for the final design and assembly of the vehicle's cabin. Figure 3-1 is a sketch of the side and end views of the chassis with an outline of the vehicle on top, which has a length/height ratio close to the famous Fibonacci ratio $\left(1+\sqrt{5}\right)/2$. Three vehicles will be in the preliminary order for the pilot system. The work needed is to

- Produce drawings and specifications from which to fabricate the cabin.
- Select and procure the necessary components.
- Assemble the cabins as finished units ready to be attached to the chassis.

3.1 Loading

3.1.1 Payload: The cabin is designed to accommodate a maximum payload weight of 800 lb.

3.1.2 Wind: The cabin shall be designed to a maximum side wind of 60 mph.

3.1.3 Passenger loads: The cabin shall withstand the load of a 300-lb passenger pushing on the interior components of the cabin. The cabin floor at any point shall withstand a 250-lb concentrated load bearing on a half-inch by half-inch area.

3.2 Exterior Dimensions

Subject to accepted reasons for change, the expected exterior dimensions of the cabin are: length 104 in, height 65 in, and width 60 in. The walls shall be as thin as practical both from the view of structural strength and heat transfer.

3.3. Accommodations

The cabin is to be designed to accommodate either a person in a standard-sized wheelchair entering from the side and turning to face forward with an attendant, three adults and two children, a person with a bicycle, two people with large suitcases, or two persons with a baby carriage.

3.4 The Floor

The interior floor of the vehicle shall be at the same level (± 0.5 in) as the station floor. It shall be covered with a durable commercial grade material that will be easy to clean. The edge of the floor at the door shall be within 0.5 in of the edge of the station floor.

3.5 Seats

There shall be a forward-facing bench seat at the rear interior of the vehicle divided into three equal sections that may be folded up individually, filling the interior width of the cabin with the backs extending to the interior top of the cabin and tilted backwards by 6^o (six degrees). The back of the seat back at the seat height shall be forward from the rear wall of the cabin 10 in to permit space for the equipment described in Paragraph 3.12. The top of each seat shall be 17 in from the interior floor and shall fold up to ease access of a wheelchair or other large object. These seats will have a spring constant of about 200 lb/in. There shall be two backward-facing fold-up seats at the front of the cabin designed to accommodate small people. These seats shall be spring restrained into the folded-up position when not occupied. The seat material will be durable, vandal proof, and fire resistant.

3.6 Door

One possible door configuration is a single inverted U-shaped automatically powered door 36 inches wide that would open by sliding back over the rear shell of the cabin and thus opens on both sides of the cabin as one unit. Other door configurations can be considered. The door shall open or close within 2.5 sec and shall be equipped with sensors that prevent closure on any object. The door operating mechanism shall be placed under the inside floor of the cabin. To ease entry of a wheelchair, the rear edge of the door shall be in line with the front edge of the bottom of the folded-up seat. The door-operating mechanism shall be designed for a life of 160,000 operations (open and close) and with no more than one failure in 50,000 operations.

The seal of the door shall be designed to prevent entry of noticeable amounts of water in a rainstorm of 2 in/hr.

3.7 Windows

The windows, front, back and sides, are to be of a plastic such as LEXAN and should be large enough to permit a panoramic view as the vehicle moves along the guideway, but not so large that they would compromise the structural integrity of the cabin. The material of the windows and the entire exterior shall withstand daily brushless washing and shall be coated to minimize entry of solar infrared energy.

3.8 Styling

Since the cabin is the one element of a PRT system seen most and is the signature of the entire system, styling is critically important. The design should, as one sculptor said, ". . . bring out the kid in you" while portraying dignity to the wealthy purchaser of the system.

3.9 Aerodynamics

Even at speeds as low as 25 mph air drag is the largest energy consumer. Also, the power to overcome air drag increases as the cube of speed. There is a substantial amount of information from wind tunnel data on shapes that minimize air drag. Since the system will operate in crosswinds up to about 60 mph, side drag is important. As side drag increases, it increases forward drag. The corners connecting the side to the top of the vehicle should be rounded with a radius of at least 10 in. For these reasons, air drag is an important consideration in the design.

3.10 Structural Design

If a U-shaped door is used, the cabin shell is composed of three parts, the front part, the back part, and the door. These parts shall be manufactured from strong, light-weight composite material with metal reinforcements as needed. When the door is open, it is possible for a strong man to push against the top of the front or back part of the cabin to see if he can break it. Therefore, as mentioned in Section 3.1.3, such a loading must be resisted well below the yield point of the material.

3.11 HVAC

A heating, ventilating, and air conditioning system shall be designed into the cabin, with the large components, such as the compressor and the drive motor, placed in the compartment behind the seat. The designer can assume that the vehicles will be stored in the shade and that the stations have a roof over the vehicles and waiting passengers. Moreover, in a PRT system, while the vehicles will be stored power off, the HVAC designer can assume that at least three minutes will pass from the time HVAC is turned on until a passenger enters, which is a more relaxed requirement than necessary in automobile design. The HVAC designer shall work with the structural designer to specify insulation in the walls that, as close as practical, will minimize the sum of the annualize cost of the wall plus the annual cost of heating or cooling energy. The ventilation system shall provide the air exchange recommended by the Society of Heating and Ventilating Engineers. The temperature in the cabin shall be controlled to the median comfort level assuming people are clothed appropriately to the outside weather.

3.12 Equipment Compartment

The computers that operate all functions will be in a compartment behind the main seat and there shall be an access door at the rear of the vehicle that can be opened by qualified personnel. The major AC components shall share the same compartment. The seat back facing the equipment compartment as well as all other components of the cabin shall be non-combustible.

3.13 Passenger and Environmental Controls

There shall be three buttons conveniently located in the vehicle that can be actuated by the passengers: a “Go” button, a “Stop” button, and an “Emergency” button. The “Go” button causes the door to close and signals to the computer that the vehicle is ready to leave the station. The “Stop” button causes the vehicle to stop at the next station and then the door to open after it is stopped. The “Emergency” button alerts a human operator located in a control station to inquire through a communications system as to the problem. If the rider indicates sickness, the operator can change the vehicle’s destination to that of the nearest hospital. If the rider is in danger, the operator can change the vehicle’s destination to that of the nearest police station. If the rider feels the temperature in the vehicle is too high or too low, the operator can adjust it, etc.

3.14 Communications

There will be a two-way communication system in each vehicle to connect an individual vehicle or a group of vehicles to the system’s control room. This system will be separate from the communication system that controls the speed and position of the vehicles, which is described separately. There will be a television screen in the front center of the vehicle near the floor. It must be possible for the passengers to turn the set on or off, and if on to switch to site-specific advertising, travel information about the passing surroundings, news, or entertainment.

3.15 Lighting

The cabin will be equipped with reading lights that can be switch on or off by the passengers. Exterior lighting is optional but low lumen so-called parking lights and red tail lights are recommended.

3.16 Attachment to the Chassis

The cabin will be built with a pair of 20in long, by 2-in wide, by 2-in deep inverted wells in its bottom at major structural cross members to permit bolting to corresponding members of the chassis as shown in Figure 3-1. As specified in Section 4, these members will be hollow so that they can accept wires to and from the chassis.

3.17 Wiring

Only moderate voltages, for example 24 or 48 volts DC, are to be transferred from the variable-frequency drives in the chassis to the cabin. A voltage bus in the equipment compartment shall be used to drive all the cabin components, I.e., the computer, the door motor, the heater, the air conditioner, the ventilation fan, the lights, the television set, the lights, the communications system, and the sensors. The wire insulation shall be non-combustible.

3.18 Fire Prevention

Fire prevention is of primary importance, which is the reason only a low voltage will be permitted in the cabin. All materials in the cabin shall be certified non-toxic and non-combustible. The cabin shall contain a smoke detector that shall cause the vehicle to stop at the next station and open the door automatically upon detecting smoke. Temperature sensors shall be placed at strategic locations in the wiring and in the electrical components to command the current to be shut off and a warning sent to central control if the temperature exceeds a preset value.

3.19 Lightning Protection

The cabin designer shall consult with the wayside power team to devise a suitable means for protecting the cabin from a lightning stroke.

3.20 Environmental Specifications

The cabin is to be designed to be operable in the expected range of exterior conditions; temperatures from -45^o C to +50^o C, salt spray, sand storms, and daily brushless cleaning.

It is expected that the cabin will be replaced once every ten years.

Minimization of the effects of vandalism must be considered in every phase of the design.

3.21 Cleaning

The cabin designer shall consider daily external and internal cleaning of the cabin, and shall select materials and designs of the interior and exterior of the cabin for easy cleaning. Since the cleaning means is a part of the system, methods that will minimize damage can be assumed.

3.22 Cabin Weight

Since the weight and therefore cost of the guideway is proportional to the gross weight of the vehicle, weight minimization of the cabin is important, if the cost of weight reduction is not more than about $30 per lb.

3.23 Standards

The cabin shall be designed to comply with the requirements of USO 9000 and NFSA 130.

3.24 Changes in the Numerical Specifications

If the cabin-design team believes that a change in one or more of the numerical specifications given above is needed, they are to bring their suggested change to the management and systems engineering team with ample justification for the change.

4. Final Design and Assembly of the Chassis

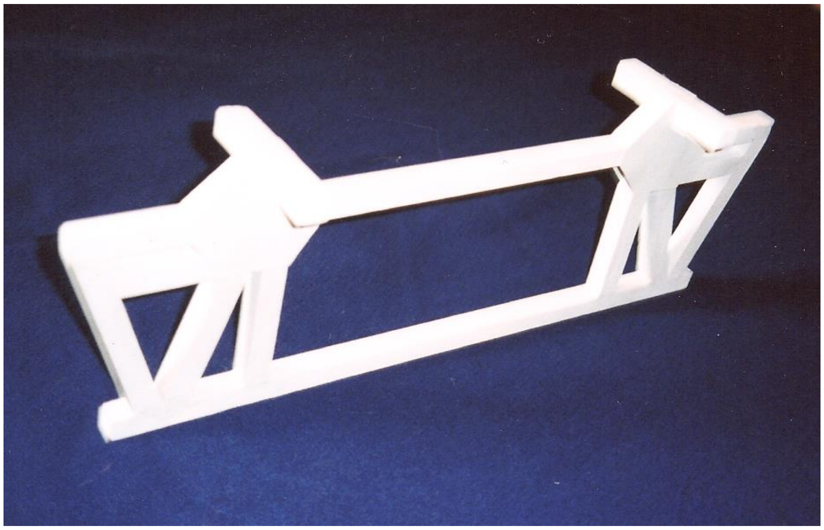

Figure 4-1. A Model of the Chassis Frame.

This specification is for the final design, fabrication, and assembly of the vehicle’s chassis. Figure 3-1 is a sketch of the side and end views of the chassis with an outline of the vehicle on top. Three vehicles will be ordered for the pilot system. The required tasks are to

1. Perform an accurate quantitative verification of the design under calculated loads[8] with modifications if necessary,
2. Produce drawings from which to fabricate the chassis frame, the switch, and all brackets and linkages,
3. Select and procure the necessary components except for the Linear Induction Motors (LIMs) and their drives,
4. Assemble the chasses as finished units ready to receive the cabin.

Dynamic analysis of the vehicle passing through merge and diverge sections of guideway with extreme wind and passenger loads verifies the maximum and steady-state wheel loads. The existing program must be revised to consider final dimensions and weights.

The chassis rides inside of a covered guideway and thus is not exposed to the sun; however, rain or snow may enter the 3-in wide slot at the top of the guideway, and the chassis must perform in wet or dry conditions in temperature range given in Section 1.16.3 in an atmosphere typically 20 feet above the ground that may contain salt, dust, or sand. Noncombustible material shall be used throughout, and the chassis is to be designed for a life time of 20 years, during which time it can be expected to travel 2,000,000 miles. The components must be easily replaceable to minimize vehicle downtime. System cost minimization requires, *inter alia*, minimum guideway weight, which required minimum vehicle weight. Thus, weight minimization of the chassis is important until the cost of weight reduction exceeds about $30 per lb. Safety and meeting required performance at minimum life-cycle cost are the fundamental design requirements.

4.1 **Frame**

The frame of the chassis, to which all the components are attached, is vertical and consists of eight 2 in x 2 in high-strength, square steel tubes[9], with rounded internal corners. The top horizontal tube is 104 inches long. Shock absorbers are secured at each end. The lower horizontal tube is 94 inches long. Plugs are to be welded into each end to increase torsional stiffness and to prevent debris from entering the tube. The distance between the bottom of the top horizontal tube and the top of the bottom horizontal tube is approximately 21 in. The exact dimension will be determined by analysis of the height needed for the 13 in nominal OD main support tires, the height and clearance needed for the switch rail, and the height and clearance needed for the 600-volt DC power rails. The top and bottom horizontal tubes are separated by six

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[8] See "Lateral Dynamics of the ITNS Vehicle."

[9] Steel has the advantage that it has a fatigue limit, whereas aluminum does not. It is easier to weld, and has a much higher yield stress. Steel has the possible disadvantage that the sections needed to keep the weight to a minimum may be so thin that their thickness would be limited by buckling, thus potential buckling must be analyzed.

tubes, two vertical, and four inclined as shown in Figure 3-1 to provide resistance in a collision between two vehicles at a relative speed of 10 mph. The frame is to be assembled by welding.

4.2 Attachment of the cabin to the chassis

The cabin is attached to the chassis at two points, as illustrated in Figure 3-1.[10] The attachment is illustrated in Figure 4.2. The top member of each of the two attachment assemblies is a 20 in long by 2 in x 2 in steel tube with squares welded into the ends to increase torsional stiffness. When the chassis is assembled, these members are inserted into two slots in the floor of the cabin and bolted firmly to the cabin floor. The joint under the top member consists of seven pieces to be bonded together with a high-strength, 4000-psi-shear-strength, epoxy adhesive, such as provided by 3M Company, and bolted. The center piece of the attachment is a block of steel 3-in longitudinally, 1.5 in laterally, and 2 in high, hollow to enable wires to be passed between the chassis and the cabin.

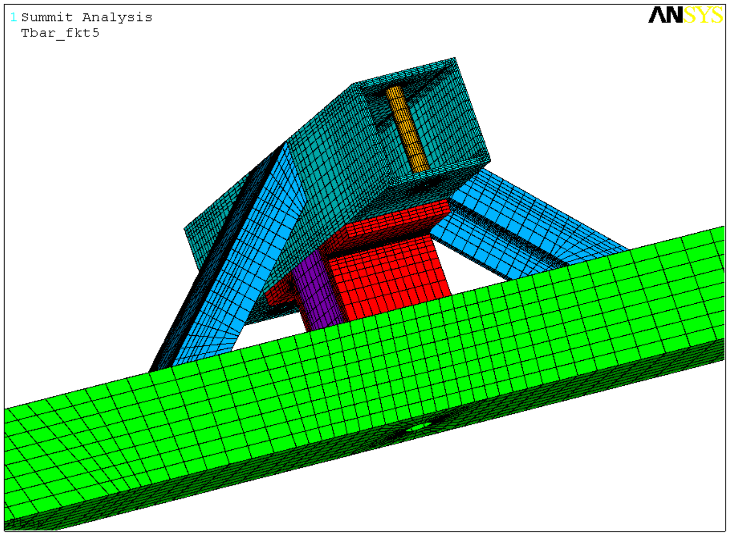

Figure 4-2. The Chassis-to-Cabin Attachment.

To this block are bonded a pair angles each 2 in wide, 2 in high, 5 -in mm long, and 0.5 in thick. These angles are to be bonded and bolted to the center piece and to each of the two 2 in long transverse tubes. Next a pair of 2 in wide channel sections are cut at 45 degree angles and are both bonded and bolted in place as shown in Figure 4.2. Finally, a pair of hexagonal 0.025 in thick sheets of the same material, of the shape shown in Figure 3-1, are bonded to the sides with cutouts for the transverse 2 in x 2 in tubes with the above-mentioned adhesive to provide the necessary shear strength. Detailed finite element analysis is needed to verify the design and can be subcontracted. In this analysis, the maximum load shall be taken as a 500-lb wind

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[10] The reason for two-point attachment is to eliminate the need to widen the guideway covers in curves.

load on the side of the cabin plus a 700-lb vertical payload offset from the center line of the cabin by 20 in. The empty cabin weight will be assumed for this analysis to be 500 lb, and we aim for an assembled chassis weight of no more than 600 lb.

4.3 Main wheels, axles and bearings

The distance between the axles of the front and rear main-support wheels is 84 in. The wheels are nominally 13 in (up to about 0.3 in more) to the outside of the tires, which are 4 inches wide. The width between the centerlines of the left and right wheels is 14.5 in.[11] Each wheel shall be designed to carry a steady load of 550 lb with double this value for about two seconds when passing through the entrance to a superelevated turn. The tires may be high-pressure pneumatic or the designer shall investigate the new Michelin airless tire that has the same properties as a pneumatic tire. The tire stiffness shall be 2200 ± 200 lb/in. Thus, the variation in deflection from a fully loaded to an empty vehicle is 900/4/2200 = 0.10”. The needed tire, wheel, bearing and axle assemblies can be purchased to order from a company such as Aerol Co., Inc., of Glendale, CA. The axles will be high-strength aluminum or steel turnings, hollow to reduce weight and to permit wires to be passed from encoders, and bolted to the chassis frame as may be seen in the end view of Figure 3-1. Sealed bearings will be used. They will each contain in the hub a digital encoder with a resolution of at least 2048 pulses per revolution, such as manufactured by Timken. The output of the left and right pairs on each of the fixed axles will be averaged to obtain position and speed, and redundancy is provided by placing encoders in all four main-wheel bearings. Note that the main wheels do not steer, which is acceptable in a light-weight vehicle with a short wheelbase, the more so as the friction of the tires decrease.[12] For reference, the Cabintaxi PRT program during the 1970s found this practice to be satisfactory.

4.4 Upper and lower lateral wheels, axles and bearings

Four upper lateral wheels provide yaw stability and four lower wheels add roll stability and symmetrical loading. While these additional lower wheels cause the chassis to be subjected to a twisting moment when passing through the entrance to and exit from a super-elevated turn, analysis[13] shows that the offset of the second set of lower lateral wheels from the plane of the other wheels is small enough to be neglected. The centerlines of the upper lateral wheels are directly above the centerlines of the main support wheels. The diameter of the four upper lateral wheels is 8 in OD and of the lower lateral wheels 6 in, both sets with solid polyurethane tires. The maximum load on a switch wheel is 1200 lb for one second. The maximum load on

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[11] “Deflection of Running Surface.” JEA Book, Task #5, 5.3.9.

[12] “Effect of Non-Steerable Wheels on Road Resistance in Curves.” JEA Book, Chapter 9, 9.17.

[13] “The Offset of the Lower Rear Wheel on the Chassis.” JEA Book, Chapter 9, 9.11.

any one of the lower side wheels is 1300 lb, and on an upper side wheel 2000 lb. The maximum steady load requirement for perhaps 5 or 10 minutes is 1000 lb each on the pair of upper lateral tires. The deflection of each of these tires should be approximately 0.2 in under a 1000 lb load. Each of these wheels shall be provided with sealed bearings and axles designed to fit brackets, to be designed, that attach to the chassis frame.

To provide a firm anchor for the upper lateral wheels, an additional piece of 2 in x 2 in square tube is welded below each of the upper wheels as shown in Figure 3-1. Brackets need to be designed to attach the wheels firmly to the frame.

Firm attachment of the lower lateral wheels requires a pair of arms as shown in Figure 3-1 plus a shear member between the upper and lower arms.

4.5 The Switch

There will be one switch arm near the front of the chassis and one near the rear as shown in Figure 3-1. The arms are slaved to each other as described below and will be thrown by rotary solenoids, such as manufactured by Johnson Electric (www.testco-inc.com/saia-burgess.html), one to throw the switch to the right and the other to the left. A 4-in-OD polyurethane-tired wheel with its bearing and axle is mounted to each end of each of the two switch arms. The maximum load on one switch wheel is 1200 lb, which is applied for only a fraction of a second. The deflection under this load shall be approximately 0.1 in. The shape of the arm is arranged so that the line of action of the force on the wheel passes through the center of the switch axle, thus making the switch arm self-centering. To make the switch bi-stable, a compression spring (leaf or helical) is mounted at the top of the center of each switch arm.[14] A finite element analysis of the switch arm with its wheels and axles is needed to determine the exact shape, material properties, and moment of inertia about the axis of rotation. The required stiffness of the spring and the torque pulse required of the rotary solenoid are determined by a dynamic analysis of the switch assembly, considering the inertia of the two switch arms and the inertia and friction of the mechanism that slaves one to the other. The center of gravity and strength of the spring must be selected so that a 0.25 g lateral acceleration will not throw the switch. To stop the moving switch arm at the correct position, a snubber, such as manufactured by Enidine, is mounted to a suitably designed bracket attached to the frame. A proximity sensor is suitably mounted to enable signaling to the control system that the switch has been thrown.

A problem in slaving the two switch arms results because the axis of the switch must be placed about two inches above the midpoint between the upper and lower lateral wheels. This determination is made by a static analysis of the maximum forces to the left and to the right as the vehicle passes through either the straight or the curved portions of a merge or diverge sec-

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[14] “Analysis of a Bi-Stable Switch.” JEA Book, Task #4, 4.8.

tion of guideway.[15] But the position of the switch axles at the center of the chassis is occupied by two variable-frequency drives and a battery. The problem is solved, for example, as follows: Weld a 2-in channel section, flat side up, about 2 in above the lower horizontal square tube that forms the lower member of the chassis frame. To increase its stiffness, add supports as needed. Under the channel section mount a horizontal tube with bearings at two or more positions along the tube to permit the tube to rotate freely. To the top end of each switch axle mount a vertical arm forked at the bottom to receive a similar arm mounted to the lower horizontal tube with a roller at the top. With identical mechanisms at both ends, each solenoid operates both switch arms, one to the left and the other to the right. Alternative mechanisms may be considered. Zero slop is not necessary because the switch arms are made bi-stable by means of the leaf springs.

The switch assembly must be tested separately under load for at least 300,000 cycles before being assembled into the chassis, and must be designed so that the maximum stresses are no more than 75% of the fatigue limit of the steel. Special attention must be placed on designing to reducing stress concentrations.

Inventory of switch parts:

1. Two switch arms
2. Four wheel, bearing, axle assemblies
3. Two switch-arm shafts
4. Two rotary solenoids
5. Two solenoid mounting brackets
6. Two leaf springs
7. Four snubbers
8. Two proximity sensors
9. One long tube mounted on bearings
10. Two upper forked arms to be fixed onto and perpendicular to the switch-arm shafts.
11. Two lower arms each with a bearing on the top end to be fixed onto and perpendicular to the long lower tube.

4.6 The LIM bogie

The LIM bogie permits the LIM to maintain a steady 0.1 in air gap to its reaction rail while permitting the vehicle to settle at different heights depending on the weight of the passengers. There is a pair of LIMs, one acting against the left running surface shown in the left view in Figure 3-1 and one against the right running surface. To the front and rear of each LIM is welded a tapered bracket with a hole at the free end to receive one of a pair of fixed axles that connect the two LIMs. As shown in Figure 3-1, two 4” OD polyurethane-tired wheels with their bearings

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[15] “The Optimum Switch Position.” JEA Book, Task #4, 4.4.

are mounted to each of these axles. These wheels must each carry a steady load of 300 lb corresponding to both the weight of the LIMs and the maximum normal force produced when the vehicle is accelerating. To each of these axles is attached a pair of horizontal links approximately 3" long. From the Pythagorean theorem, if the link length is a and the vehicle can move up or down a total of δ then motion either up or down is $\delta/2$ and the slop the bearing at each end of the link must have is $(\delta/2)^2/2a/2=\delta^2/16a$. If δ is say 0.25" and $a=3$" the bearing slop required is only 0.0013," which is less than can easily be achieved. The other end of each of these four links is attached with a journal bearing to a vertical bracket that is fixed to the lower frame member.

An alternative to this design is to sense the air gap and adjust it by means of servos at each of the four corners of the LIM assembly. Before investigating such a solution, data needs to be obtained from the LIM supplier on the effect of air gap on thrust and efficiency.

4.7 The Parking Brake

Normal acceleration and braking is applied via the LIMs; however, when the vehicle stops in a station we must turn off the power to the LIMs, in which case it would be easy to move the vehicle either because of a wind or human force. Thus, there must be a parking brake that will hold the vehicle in position. The parking brake also serves as an emergency brake while the vehicle is moving and the rare circumstance occurs in which emergency braking is needed but the redundant LIMs, drives, or power supply has failed.

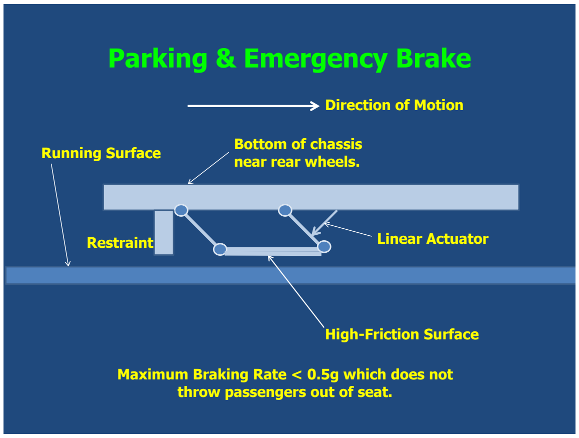

Figure 4-3. The Parking and Emergency Brake.

Because it is possible though improbable for the wayside power to fail, the parking brake must be powered by the on-board battery. Power must be applied to the brake only when it is operated. With the brake either fully applied or not applied the power to the brake motor must be switched off. These features are achieved with the arrangement shown in Figure 4-3 just ahead of the rear wheel. A pair of brake shoes, one acting on the left running surface and the other on the right, are horizontal members with a high-friction material bonded to the lower side. A pair of links of identical length support each brake shoe at its front and rear. In this way any motion of this assembly keeps the shoe parallel to the running surface. The assembly can be actuated by a ball-screw actuator of standard design, which can be chosen so that the actuator will not back up when turned off under load. There must be a stop that prevents the assembly from moving backwards past the vertical position. Each of the two brakes must be designed to resist a maximum vertical force of 650 lb, and a maximum horizontal force of 250 lb.

4.8 Shock-absorbing bumpers

As illustrated in Figure 3-1, there shall be a 4-in-stroke shock-absorbing bumper of standard design mounted at the front end of the upper horizontal square tube and a friction shock. The front shock shall be a constant-force, constant-displacement, spring-return device such as supplied by EGD Inc. The ends shall be configured to engage in a turn down to a radius of 36 ft. The shock absorber shall have the highest practical in-lb rating.

4.9 Power pickup

For propulsive power, the vehicle will be supplied with 600-volt DC from power rails mounted inside the guideway as shown in Figure 3-1. A pair of power-pickup shoes attached to each side of the chassis carry the power to the variable-frequency drives. A special problem in a PRT application is that one of the pairs of shoes must disengage and then reengage as the vehicle passes through a merge or diverge section of guideway. Thus, there is a potential problem of chattering and hence sparking and excessive wear. Fortunately, this problem has been studied experimentally at the Insul-8 facility in Omaha, NE, and found to have a satisfactory solution.

The chassis designer shall coordinate with System Engineering and the power-supply engineer to design the attachment of the power pickup shoes to the chassis.

4.10 Transmitter/receivers

Information is carried from the vehicle’s computer to the cognizant wayside zone controller and back via a leaky cable mounted inside the guideway. The information-transfer device is a pair of transmitter/ receivers mounted to the chassis. The chassis designer shall coordinate with Systems Engineering and the electronics engineer to design the required mounting means.

4.11 Variable-frequency drive (VFD) mounting

A pair of VFDs are mounted in the chassis. They are the boxes shown in Figure 3-1. The chassis designer shall coordinate with Systems Engineering and the VFD supplier to design the required mounting means.

4.12 Battery mounting

A battery to be specified by the power-supply engineer is to be mounted near the middle of the chassis between the two VFDs as shown in Figure 3-1. It is to provide uninterruptible power to the on-board computer, the HVAC system, the switch, the parking brake, and other auxiliary devices. The chassis designer shall coordinate with Systems Engineering and the power-supply engineer to design the required mounting means.

4.13 Wiring

The chassis designer shall coordinate with Systems Engineering to design the attachments for all the necessary wiring among chassis components and between the chassis and the cabin. Removing any chance of fire is of fundamental importance in placement and insulation of the wires.

4.14 Sensors

For test purposes, strain gages and possibly other sensors will be placed at strategic points on the chassis as determined by finite-element analysis.

5. Final Engineering for the Guideway and Posts

References

1. “The Future of High-Capacity Personal Rapid Transit.” JEA Book, Chapter 10.
2. “An Intelligent Transportation-Network System.” JEA Book, Chapter 12.
   Internal Documents:
3. “Description of Test Track.” JEA Book, Task #5, 5.2.10.
4. “The Guideway for an Intelligent Transportation Network System.” JEA Book, Task #5, 5.2.3.
5. “The Equivalence between an Earthquake Load and a Wind Load on a PRT Guideway.” JEA Book, Task #5, 5.5.
6. “Ride Comfort on a Sinusoidal Surface.” JEA Book, Task #5, 5.2.5.
7. “Running Surface Stiffness and Tire Ellipticity Requirements for Adequate Ride Comfort.” JEA Book, Task #5, 5.2.6.
8. “The Joint between Guideway Sections.” JEA Book, Task #5, 5.2.9.
9. “Support Posts.” JEA Book, Task #5, 5.3.6.

The overall concept is described in References 1 and 2. This specification relates to final design verification of the guideway-post system, preparation for its fabrication, cost estimation for fabrication, and fabrication. The three-dimensional test-track layout is described in Reference 3, and the guideway with its maximum loading conditions is described in Reference 4. References 5 through 8 provide further information about the guideway design.

To operate the Linear Induction Motors a sheet of copper 2 mm thick and 250 mm wide must be attached to the horizontal, 7.5” wide, surface of each of the main-wheel-support angles and overlapped underneath. Since the wheels mounted on the chassis do not steer, there will be some wear while traversing the curves in the guideway. Tests performed at Raytheon in 1993 relieved concerns about wear on the copper surface; however, using principles of tribology further analysis and testing of expected wear on the copper surface is warranted. A great deal of information about tribology can be found on the Internet including references to possible consultants. Such a consultant shall be engaged to advise the project.

This project requires the assistance of an engineering company that has the computer tools and skill required to perform an accurate verification of the design, and the tools needed to produce drawings from which to fabricate the straight and curved sections of guideway. It is expected also that the selected company will assist Systems Engineering in discussions with the fabricator. An additional firm may be needed to design and build adjustable fixtures that will lay up the guideway sections for fabrication, and the fixtures needed for robotic welding. The posts (Reference 9) on which the guideway will be mounted are up to 90 ft apart. To ease transportation to the test site, the guideway may be fabricated in 45-ft sections and welded at the test site to form each of the required 90-ft sections.

The guideway shall be clamped to the posts using the assembly illustrated in Figure 5-1. Expansion joints (Reference 8) shall be placed at the 20% point in each span. The posts are planned to be bent up from 5/16” steel plate. They are to be octagonal and tapered from 10” at the top to 20” at the base, where each of them is to be welded to a 2” thick steel base plate, which is to be bolted to a reinforced concrete foundation in which four 1.5” high-strength steel studs, spaced at the four corners a square 24” on a side, are mounted to receive the base plate.

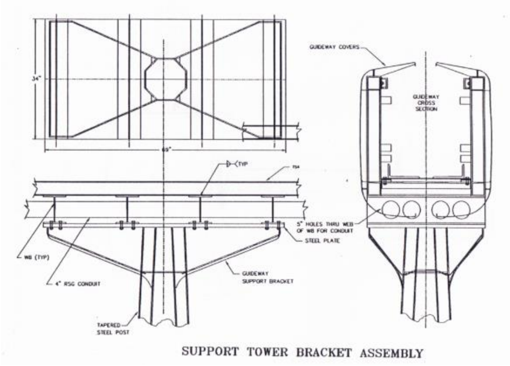

Figure 5-1. Support Tower Bracket Assembly.

The length of each post will be given. Manufacture of such posts is a specialty item. One of the few manufacturers in the United States is Millerbernd Manufacturing Company of Winsted, Minnesota. They would supply the complete post with the bracket on top and the steel base on the bottom.

The post-to-guideway bracket has been designed roughly and requires verification via finite-element analysis.

Brackets are to be designed and built into the guideway to permit a hinge attachment of the guideway covers at the bottom and a latch attachment at the stop, so that the covers can be swung down to permit access to the guideway, however remote the need to do so may be.

6. Final Design and Fabrication of Guideway Covers

The overall concept is described in the References given in Section 5. This specification relates to design and fabrication of covers for the guideway, which must be built in sections of convenient length and curved to conform to the shape of the guideway. The three-dimensional layout of the pilot system, to which the covers must be attached, will be given. The guideway with its maximum loading conditions is described in Section 5. Figure 6-1 shows a cross sectional view of the cover as it is hinged to the bottom of the guideway and secured at the top, and Figure 6.2 shows an application.

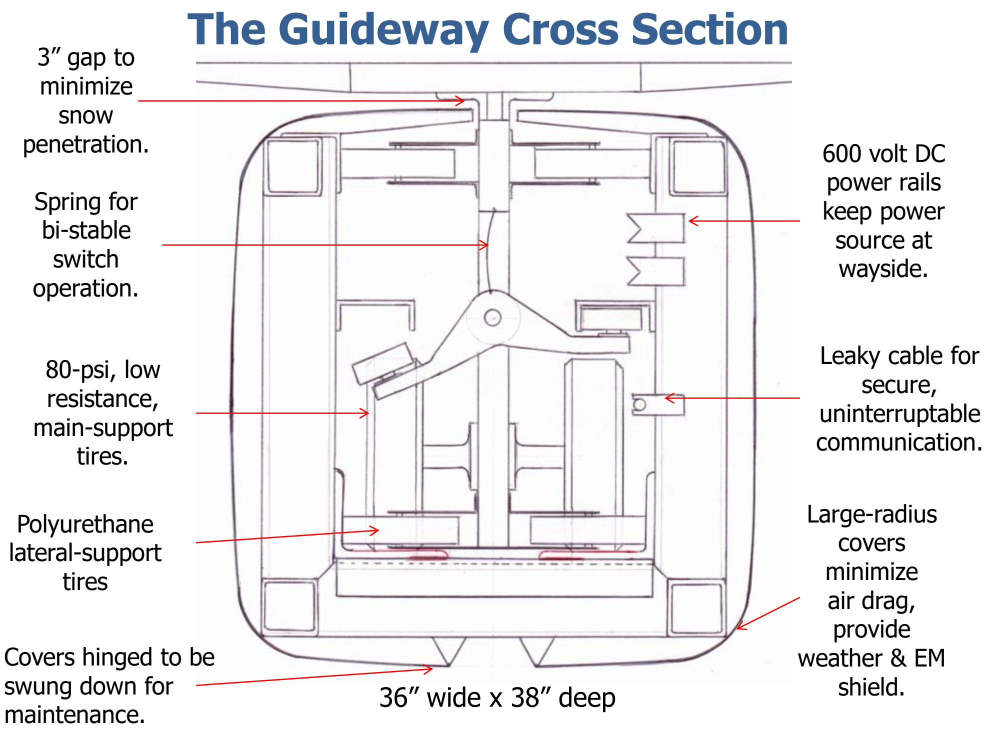

Figure 6-1. The attached guideway covers.

The radii at the top and bottom corners of each cover is 6 inches and the sides should be slightly bowed to add strength. We envision the covers to be molded from fire-resistant reinforced composite material suitable for an outside environment in which temperatures may swing from 50° C to -45° C. The exterior of the cover must be able to accept a color and texture specified by a planner, and a thin layer of aluminum is to be sprayed on the inside to act as an electromagnetic shield. The thickness of the covers must be sufficient to ease the process of lowering the cover in the field for possible maintenance inside the guideway in winds up to 12 mph. We envision a cover thickness of 3 to 4 mm. The covers are to be designed to be replaced no more than once every 20 years. The cover is to be fabricated with stainless steel inserts suitable for attachment at the top and bottom of the guideway to brackets fabricated into the guideway structure.

Figure 6-2. A possible application of the guideway covers.

7. The Design and Assembly of the Control System

References (#1-#10 are included in the JEA Book)

1. J. E. Anderson, “The Future of High-Capacity Personal Rapid Transit,” Advanced Automated Transit Conference, Bologna, Italy, November 2005.
2. J. E. Anderson, “PRT Control,” *Journal of Advanced Transportation*, 32:1(1998):57-74.
3. J. E. Anderson, "Safe Design of Personal Rapid Transit Systems," *JAT*, 28:1(1994):1-15.
4. J. E. Anderson, "Synchronous or Clear-Path Control in Personal Rapid Transit," *JAT*, 30:3(1996):1-3.
5. J. E. Anderson, “Longitudinal Control of a Vehicle,” *JAT*, 31:3(1997):237-247.
6. J. E. Anderson, “Simulation of the Operation of a PRT System,” *Computers in Railways VI*, WIT Press, Boston, Southampton, 1998, 523-532.
7. J. E. Anderson, "Dependability as a Measure of On-Time Performance of Personal Rapid Transit Systems," *JAT*, 26:3(1992):101-212.
8. J. E. Anderson, “A Review of the State of the Art of Personal Rapid Transit.” *JAT*, 34:1(2000):3-29.
9. J. E. Anderson, “Overcoming Headway Limitations in PRT Systems,” PodCar Conference, Malmo, 9-10, December 2009.
10. J. E. Anderson, “Failure Modes and Effects.”

11. Vehicle Control Software.
12. W. E. Greve, D. E. Haberman, and R. P. Lang, "Advanced Group Rapid Transit Vehicle Control Unit Design Summary," Final Report, May 1985, Boeing Aerospace Company, DOT-UT-80041.

This specification is for the design, assembly, and test of the control system needed to operate *ITNS* vehicles on a full-scale pilot system.

7.1 Background

ITNS is our name for a type of transit system generically called High-Capacity Personal Rapid Transit. Serious work on the design of control systems required for HCPRT extends back to the 1960s. Reference 1 gives a bibliography of articles on control of HCPRT. Reference 2 describes the *ITNS* control concept as it had advanced by 1996. Reference 3 describes the elements of safety and why linear-induction motors are necessary. Reference 4 shows why synchronous control is not a viable option for any but a very small system. Reference 5 shows that only speed and position feedback are needed to control an *ITNS* vehicle and derives the gain constants needed in terms of a natural frequency, a damping ratio, a first-order thruster lag, and the mass of the vehicle. Reference 6 describes the operation of ITNS vehicles in a network of guideways. Reference 7 defines *Dependability* and shows why it is the most useful measure of on-time control. Reference 8 contains important information about control in a systems context. Reference 9 shows how very high safety and reliability can be obtained. Reference 10 calculates the MTBFs of many potential failure modes and in the process, gives useful information on how the control system works. Reference 11 is the vehicle-control software program as it stands today. Reference 12 is the final report of a detailed study of control of automated transit vehicle done by Boeing Aircraft Company for the U. S. Department of Transportation. This contract work forms the basis for the ITNS control system; which, however, is markedly improved because of advances in technology in sensing of speed and position, in communication means, and in increased speed and memory of microprocessors.

The details of *ITNS* control have been developed and form the basis for the current project, in which we need to consider further advances in technology that may improve performance and/or lower costs. As mentioned, we obtained a significant amount of information from Boeing on their control work under the federal Advanced Group Rapid Transit program, which is described in a series of articles in IEEE publications, which are available. During the past few years, we have developed the software programs needed to operate an *ITNS* network of any complexity.

7.2 **The Control Concept**

Control is accomplished by means of three levels of computers: Computers on board each vehicle (VC), wayside zone controllers (ZC), and a central controller (CC). Each VC receives commands from the local ZC and transmits to it position and speed. The CC communicates with each ZC, but not with the VC.

There are five types of zone controllers (ZC):

1) Each station ZC, SZC, controls the movement of vehicles through and around a station.
2) Each merge ZC, MZC, controls the operation through each merge section of guideway.
3) Each diverge ZC, DZC, controls each diverge section.
4) A line ZC, LZC, may be needed in a section of guideway too long to be included in one of the other types.
5) The fifth type of ZC, PZC, manages the flow of passengers in a station.

The number of vehicles that can be accommodated in each ZC depends on the data rate. The amount of data that must be transmitted is minimized as described below. The VCs and ZCs are used repeatedly without change as the network grows

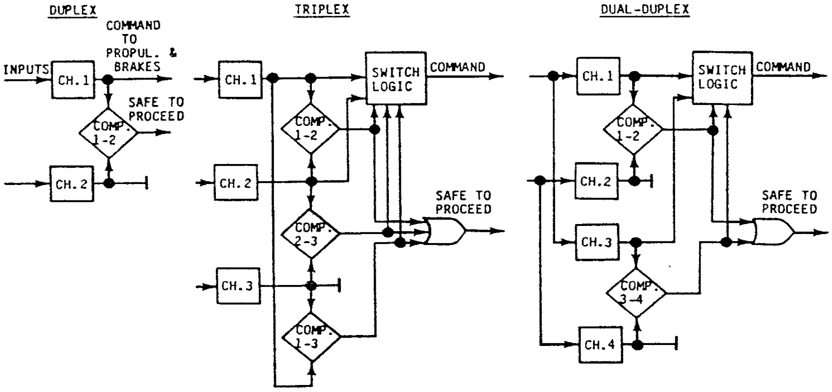

FIGURE 3: MICROPROCESSOR REDUNDANCY CONFIGURATIONS

Source: "Effects of System Architecture on Safety and Reliability of Multiple Microprocessor Control Systems." Robert C. Milnor and Roy S. Washington. Boeing Aerospace Company.

Figure 7-1. A Dual-Duplex Computer System.

7.3 Dual-Duplex Computers

During a study of automatic control for the U. S. Federal Advanced Group Rapid Transit program, Boeing found that the best way to meet a federal safety requirement was to use two pairs of motherboards in each computer making the same computations and arranged so that the two outputs of each pair must match, and then the common output of each pair must match, otherwise defensive action must be taken. They called this DUAL-DUPLEX (see Figure 7-

1). ITNS uses this philosophy in all computers in its system. The Boeing work is described in a series of IEEE papers, which are referenced in Reference 2 and in a series of reports in the public domain. The defensive actions required are discussed in Reference 10.

7.4 The Vehicle Controller

Figure 7-2 is a block diagram of the vehicle controller. The gain constants G_v and G_p are derived in Reference 5. The vehicle is propelled and braked by a pair of LIMs, each of which receives a variable-frequency voltage input from a Variable Frequency Drive (VFD), which receive its command voltages from a software package that calculates the instantaneous required frequency and voltage.

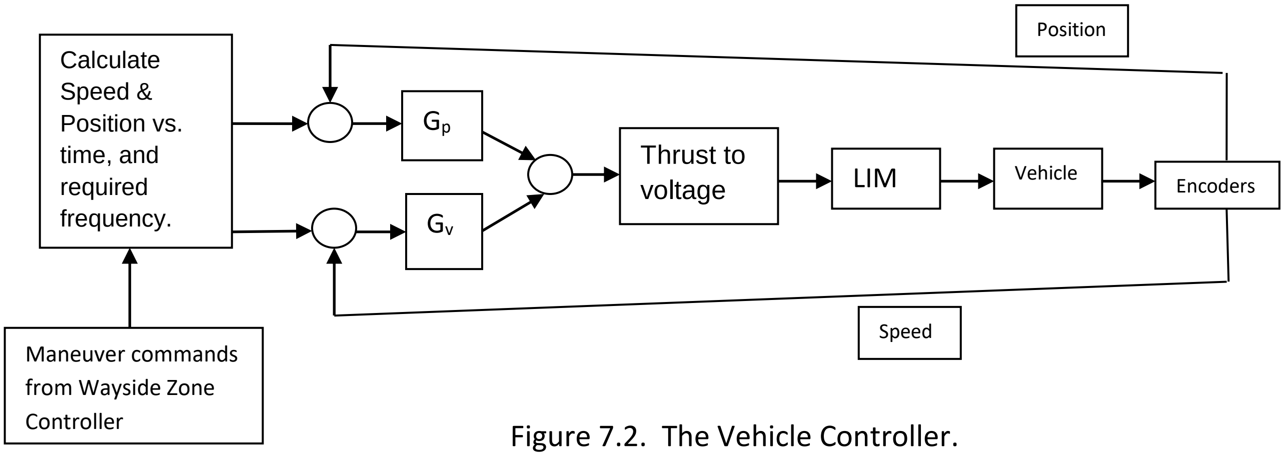

Figure 7.2. The Vehicle Controller.

The frequency is a predetermined linearly increasing function of speed. Conversion of thrust commands into voltage commands is accomplished by use of an equation that calculates the required voltage as a function of thrust, slip, and frequency. When operating at a constant speed, the vehicle computer receives the command speed from a wayside zone controller (described below) each time-multiplexing interval. If the speed signal is not received in two successive intervals, the vehicle is commanded to a creep speed of about 1 m/s, at which a collision is of no consequence (Each vehicle is equipped with shock-absorbing bumpers front and back.)

A wayside ZC transmits to a specific vehicle a maneuver command with a parameter, such as "Stop in x meters." The vehicle controller has in its software the subroutines needed to calculate the instantaneous speed and position required of any maneuver. It compares these command values with the actual speed and position 200 times per second. The differences are multiplied respectively by a speed gain and a position gain, summed, and then sent as a thrust command to a thrust-to-voltage converter.

Position and speed can be obtained from digital encoders, which can be imbedded in the wheel bearings. The left and right encoder outputs are averaged to give the correct output in turns, and the fore and aft encoders provided redundancy. The accuracy of encoders has been shown to be sufficient to obtain speed by differentiating the encoder output.

In a project for the Chicago RTA in 1991 that involved Raytheon and Hughes engineers, it was determined that the most secure way to transmit data between the vehicles and the wayside zone controllers was via a leaky cable mounted inside the guideway. They are now commercially available. Devices that transmit and receive data to and from the communication means need to be designed, built, installed, and tested.

7.5 Switch Operation

The switch consists of a pair of arms with a polyurethane tired wheel on each end as shown in Figure 7-3. They rotate about a longitudinal axis. In merge and diverge sections of the guideway switch rails are positioned to intercept the switch wheels, thus constraining the vehicle positively as it passes through the merge or diverge section. The switch consists of a pair of arms with a polyurethane tired wheel on each end as shown in Figure 7-3. They rotate about a longitudinal axis. In merge and diverge sections of the guideway switch rails are positioned to intercept the switch wheels, thus constraining the vehicle positively as it passes through the merge or diverge section. The switch is rotated by means of a pair of rotary solenoids, one of which throws the switch to the right and the other to the left. The switch arms are held in one of two stable positions by a pair of leaf springs, and their motion is stopped by a pair of commercially available snubbers. If the switch arm is rotated so that the left wheel is horizontal, it is set to steer the vehicle to the left, and if rotated so that the right wheel is horizontal, it is set to steer the vehicle to the right. The position of the switch is sensed by means of a pair of proximity sensors wired to the VC. When the VC receives a switch command from a cognizant wayside ZC, it determines if the switch is in the desired position or if it must be thrown. If the latter, the VC commands a pulse of current to one of the rotary solenoids, and at the same time commands the vehicle to creep speed about one second later. The action of the switch arm reaching the other position (in about 0.25 sec) is sensed by the cognizant proximity sensor, which informs the VC to cancel the signal to slow the vehicle to creep speed. This is one of the ways in which fail-safe operation is implemented.

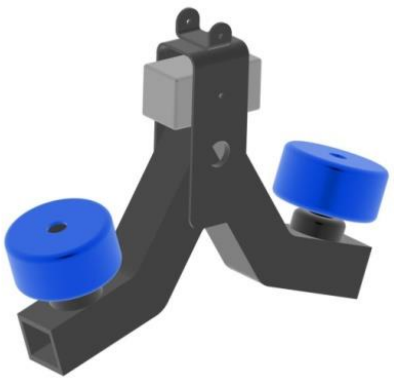

Figure 7-3. A Switch Arm.

7.6 Auxiliary Functions of the VC.

The VC on each vehicle

- commands opening and closing of the door,

- accepts and stores the destination command,
- changes the destination command if requested by the occupant or by a central operator,
- controls the lights,
- controls the HVAC system,
- senses and responds to overloading,
- senses and responds to smoke in the cabin by causing the vehicle to stop at the next station, alert authorities, and upon stopping causes the cabin door to open,
- keeps track of distance traveled to direct itself to maintenance on a predetermined schedule,
- senses incipient failures by means of strain gages, temperature sensors, pressure sensors or vibration sensors and, based on established criteria, dispatches the vehicle to maintenance after causing the passengers to unload, and
- stores information on all failures for analysis of the mean time to failure.

7.7 Vehicle Control Program

A computer program has been written to operate the vehicle under the closed-loop control system shown in Figure 7-2. The position and speed commands are derived to cause the vehicle to perform each maneuver at maximum comfort acceleration and jerk and in minimum time. A computer program has been written and tested over 30 million times with random inputs to calculate each maneuver with specified input parameters.

7.8 Station Zone Controller (SZC)

A SZC controls the vehicle operations through each station, which requires information on the position and speed of each vehicle under its jurisdiction. It keeps track of the position and speed of each vehicle from the downstream point of merge of the station-bypass guideway with the main guideway upstream to the nearest branch point, whether it is the exit of another station or a line-to-line merge or diverge. The upstream ZC informs its downstream neighbor of the arrival of each vehicle in a “hand-off” operation. The downstream neighbor informs its upstream neighbor when a vehicle in its jurisdiction must slip past the zone boundary to avoid violating the minimum allowable headway to a downstream vehicle. Slip is discussed below in the paragraph describing the merge zone controller.

At a pre-calculated position upstream of each station there is a Switch Command Point (SCP). When a vehicle passes this point, its destination is transmitted to the SZC, which determines if is to be switched into the station. Normally, if the destination matches the station number the vehicle is switched in and at the same time the forward-most empty berth is reserved for it.

But the station may be so full of vehicles that it can’t accept another, in which case the SZC commands the vehicle to switch away from the station in an action called a “wave off.”

Farther down the guideway, but ahead of the station, there is a Deceleration Command Point (DCP) at which a vehicle committed to enter the station is caused to begin a deceleration maneuver to stop it at the reserved berth. But before the deceleration command, the SZC notes if there is now a free berth farther downstream, in which case it changes the berth reservation to the new forward-most free berth. At the instant the vehicle reaches the DCP it may be moving at a speed lower than the line speed and it may be accelerating or decelerating while performing a slip maneuver. Thus, the maneuver command must take into account the initial speed, initial acceleration, and the distance to stop. Such maneuvers have been programmed and thoroughly checked.

While in the station area, a vehicle may be commanded to advance to a newly freed berth, and it may be so commanded while it is engaged in a deceleration maneuver or in a station-advance maneuver. So, the SZC must follow the motion of all vehicles in its jurisdiction and be ready to command station-advance maneuvers when required. If the vehicle is in the unloading and loading area, the SZC must determine when it can advance, not only based on availability of a free berth ahead but on the status of loading or unloading.

When the first vehicle in the station area has been given a destination to a different station, it may be at rest or it may be in a station-advance maneuver to the forward-most free berth. In either case, the SZC, which keeps track of the positions of all of the vehicles bypassing the station, calculates the position in the line and the time of arrival at line speed if it were to accelerate to line speed at each moment of calculation. The SZC calculates the minimum distance to the vehicle ahead on line and the vehicle behind, and only if these distances are within acceptable bounds does it command the vehicle to line speed. The complete set of acceleration-to-line-speed maneuvers has been programmed and thoroughly checked with arbitrary initial speed and acceleration. An additional condition for commanding a vehicle to line speed is that the vehicles bypassing the station are not slipping. Slipping indicates that there may be too much traffic trying to enter a downstream merge, so the system manages excessive congestion by holding vehicles in stations until the congestion has cleared.

When there is an unneeded empty vehicle in the first berth in a station the SZC will give this vehicle the destination of the nearest storage station, whereupon it is released from the station exactly as any other vehicle is released. While the empty vehicle is cruising on line it may be redirected into a station where an empty vehicle is needed. This process is discussed in Reference 8.

7.9 Passenger-Movement Zone Control (PZC)

In each station, there is a computer that controls all functions involved with 1) passengers paying fares, 2) entering their destinations so that they can be transferred to a VC, 3) causing the vehicle door to open, and 4) determining at which berth passengers should prepare to load. The later can be indicated by a green light over the berth. By means of motion detectors, the station computer can estimate the rate of arrival of passengers from the street so that the system can be alerted to send more empty vehicles.

7.10 Merge Zone Control (MZC)

At a predetermined distance upstream of each line-to-line merge point resides a Merge Command Point (MCP). The MZC keeps track of the positions and speeds of all vehicles within its jurisdiction. When a vehicle passes the MCP, the MZC checks the positions of the vehicles on each branch of the merge. If a conflict would occur with a vehicle too close ahead on the other branch of the merge, the MZC commands that vehicle to slip back a distance sufficient to increase the headway to the accepted value. In a slip maneuver the vehicle is commanded to follow a maneuver profile in which it first slows down then speeds up to the original speed. If in slipping, the MZC detects that the headway to the vehicle behind would be too small, the MZC simultaneously causes that vehicle to slip – usually a lesser amount. This slipping of upstream vehicles continues until the next upstream vehicle is far enough behind so that the headway criterion is not violated. Slipping may continue upstream of a line-to-line merge or diverge. If the upstream branch point is a merge, vehicles on two upstream branches may have to slip. This action has been programmed. A key factor in this action is that the MZC must keep track of the slip remaining for each vehicle so that it commands only the additional slip needed to avoid conflict. The slip maneuver is designed to retard each vehicle from an arbitrary speed and acceleration. All such slip maneuvers have been programmed and thoroughly checked.

7.11 Diverge Zone Control (DZC)

Each DZC contains a table of switch commands for every station in the network. These commands may be changed by CC because of excessive traffic in certain parts of the network. When a vehicle reaches the Diverge Command Point (DCP), which is located at a predetermined distance upstream of the merge point, the DZC requests the vehicle's destination, looks up the corresponding switch command, and transmits it to the VC, whereupon the VC performs all of the actions described above. The distance of the DCP upstream of the clearance point[16] ahead of the diverge point is the line speed multiplied by a conservative estimate of the switch throw

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[16] The point at which vehicles on opposite branches of the diverge would touch each other.

time plus the distance required to stop if the VC can't detect that the on-board switch is in one or the other of the two stable positions.

7.12 Line Zone Control (LZC)

If there is a region of the guideway too remote to be served by one of the above three types of ZC, the function of the LZC is to transmit the line speed to the vehicles in its jurisdiction, to monitor the positions and speeds of the vehicles, and to remove the speed signal if one of the positions or speeds has deviated from the expected values by a predetermined amount. The result is that the VCs, lacking the speed signal, automatically slow the failed vehicle and those behind it that would be impacted to the predetermined creep speed. This monitoring function is also a function of the other three types of ZC.

7.13 Central Control (CC)

The CC is connected by fiber optics to each of the ZCs. Its function is to reduce traffic congestion when necessary and to gather and analyze data. Management of congestion requires that the CC keep track of all the vehicles in the network by data transfer from the ZC and determine by established criteria when to change the switch tables for certain destinations from certain diverge points. This function has not been programmed into the network simulation program and can be delayed until the planned network becomes large enough so that it is needed.

The CC will gather data on failures in each vehicle and the difference between each actual trip time and the expected value in order to calculate, via the method derived in Reference 7, the system dependability, which can be used as one of the means of determining if the system meets contracted on-time performance.

7.14 Network Control Program

Of the above-described controllers, all but passenger-movement control has been programmed and checked in a network control program. The program permits different speeds in different parts of the network. The simulation program is described in Reference 6.

7.15 Fault-Tolerance Means

- The wayside zone controller (ZC) emits a speed signal every 100 ms.
  With no speed signal the vehicles in its jurisdiction are programmed to creep speed.
- ZC receives position and speed from each vehicle every 100 ms.
  With no communication from a vehicle, ZC removes speed signal for that vehicle and those behind it.

- All commands are returned and verified before action is taken.
- Temperature sensors warn system of thruster failure.
- Emergency-brake command ON unless OFF received every 100 ms.
- Throw of switch commands creep speed in 0.5 sec unless canceled by signal from proximity sensor.
- Sonar or radar back-up emergency control.

7.16 System Control

The pilot system will use at least two wayside zone controllers, one of which will be the station zone controller and the other can be called a line-zone controller, which will command and monitor the section of guideway from the guideway merge point out of the station approximately half way around the track, thus permitting the implementation and testing of the process of handing off information from one zone controller to the next.

7.17 Data to be Transmitted

1. From wayside zone controllers: the speed command every Time Multiplexing Interval (TMI)[17] and maneuver commands when needed. In case of a fault, the zone controller removes the speed command, in which case the vehicles are programmed to decelerate to creep speed.
2. From the vehicles, ID number, speed, and position every TMI. If a vehicle does not receive a speed command in two successive TMIs, it and the vehicles upstream of it are programmed to reduce speed to the creep speed.

7.18 The Hardware Components

1. Position and speed detection devices mounted on each vehicle, for example digital encoders.
2. Transmitter/Receivers to be mounted on the vehicles and at wayside.
3. The communication means, most likely a leaky cable.
4. Means such as wayside magnetic markers to provide independent checks on the speed and position of each vehicle for the wayside zone controllers.
5. The vehicle and wayside computers to be used.

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[17] This need not be a fixed interval.

7.19 Information to be obtained by the Control Team

1. Data rate. The practical, verifiable data rate that can be used.
2. Time-Multiplexing Interval. From the Boeing work, available in a series of IEEE papers, the basic communication scheme was to establish a "time-multiplexing interval" (TMI) which would be divided into segments assigned to each individual vehicle within the domain of one zone controller.[18] If this is still the best practice, the TMI must be selected. It must be short enough to provide adequate position and speed monitoring but long enough so that the data can be transmitted and received without error. Boeing used 40 ms and Raytheon 200 ms assuming more vehicles. The problem here is to determine an acceptable TMI if each wayside zone controller is to handle at least 30 vehicles.
3. Frequencies. The suitable frequency range for data transmission. Boeing used 100-150 kHz.
4. Wayside Sensors. Specifications for the independent means to be used by the wayside zone controllers to verify vehicle speeds and positions, such as magnetic markers.
5. Vehicle Sensors. Specifications for the means for the vehicles to obtain speed and position information. We have tested and simulated the operation of digital encoders, and know that they would be satisfactory. An alternative method must be clearly superior at lower cost.
6. Communication Means. Specifications for the means of communication between vehicles and wayside. If there is an acceptable alternative to a leaky cable it must be less expensive and secure.
7. Common-Cause Failures. Boeing recommended using dual-duplex computers, which are defined in detail in their IEEE papers and are illustrated in Figure 7.1. In such a system, there must be no way for the system to introduce common-cause failures. Clarification of the means to ensure that common-cause faults cannot be introduced is needed.

7.20 Hardware Procurement and Installation

The control team shall program the necessary software, procure the necessary control hardware, supervise installation on the pilot system, and be available during the test program to adjust as needed.

7.21 Deliverables

- Complete specifications for the hardware components of the PRT control system.
- The required software.
- Procurement and installation of all control hardware.
- Supervision of installation of the control hardware and software.
- Consulting as needed during the test program.

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[18] These need not be equal intervals. What is essential is that each vehicle in the zone can transmit its data to wayside every TMI.

7.22 Decisions Needed During the Pilot Program

The pilot program will involve only three vehicles and one off-line station. But much of the complexity of a large system needs to be considered to prepare for commercial operation. In preparation for the pilot program the following must be selected:

- The operating system.
- The programming language.
- The means of communication between vehicles and wayside – absolute security is a key requirement (most likely a leaky cable inside the guideway).
- The required data rate between vehicles and wayside zone controllers.
- The time-multiplexing interval if a specific time interval is needed.
- The computers to be used.
- The means of position and speed sensing (likely digital encoders).

8. The Propulsion System

This specification relates to the specification, procurement, installation, and testing of the linear induction motors (LIMs) and variable voltage, variable frequency drives (VFDs) that will propel and brake each ITNS vehicle.

8.1 Configuration

Figure 3-1 shows the vehicle configuration with the LIMs mounted at the bottom of the chassis, which is inside the guideway. The vehicle is suspended by four main wheels that run on the horizontal surfaces of a pair of 8 in wide by 6 in high by 1/2-in thick steel angles. Lateral support for the vehicle is obtained by means of four side wheels near the top of the guideway and four near the bottom. The reaction surface for the LIMs is the horizontal surfaces of the angles. The LIMs are placed between the front and rear sets of main-support wheels, and are supported as a set by four 4-in OD polyurethane-tired wheels, which are attached to the chassis via horizontal linkages, which enable maintenance of a gap of 3 mm between the undersurface of the LIMs and the top surface of 10-in wide copper sheets attached to and wrapped around the main-support angles. In a vertical curve, the gap may reduce to 1 mm or increase to 5 mm for a small fraction of a second. The VFDs are to be mounted in the cross-hatched area shown in the side view in Figure 3-1.

Figure 7-2 shows the placement of the LIMs and VFDs in the vehicle's control loop. On the left, the command position and speed are compared with the measured values of position and speed, with the differences multiplied by gain constants and added. The resulting signal is a command to change thrust, which in the VFD is converted into a voltage and frequency command.

8.2 Design Constraints

8.2.1 <u>LIM Length.</u> With the chassis as shown in Figure 3-1, the LIMs may be a maximum of 38 in long. If they need to be longer to meet the performance requirements, the chassis will be lengthened accordingly, but only after other alternatives to increase performance are considered.

8.2.2 <u>LIM Cross section.</u> As mentioned above, the LIMs react against the horizontal surfaces of 8x6x1/2-in steel angles. The inside vertical surfaces of the pair of angles are 21 in apart and with the 1/2-in thickness of the angles there remains a 7 1/2 in horizontal surface on each. Per supplier recommendation, the horizontal reaction surfaces are to be covered by 2-mm-thick (0.080”) 10”-wide copper sheet with the copper sheet folded around the inner leg of the angle and underneath it. With this thickness the normal force will be roughly equal to the thrust.

8.2.3 <u>LIM Air Gap.</u> The air gap between the bottom surface of the LIM and the top surface of the copper sheet is nominally 3 mm. The LIMs will clear the inside vertical surfaces of the angle running surfaces by at least 5 mm, except in merge and diverge sections of guideway where one of the vertical angle surfaces moves away by a large amount.

8.2.4 <u>LIM Side Gap</u>. This problem is considered in[19], in which it is shown that the present design assumes a minimum curve radius of 75 ft, which means that the speed in curves must be 20 mph or greater. In the ITNS design, tighter turns are not needed operationally. In maintenance shops, where in some systems, tighter turn radii are used, in *ITNS* the lateral transfer table is used, which is much less expensive.

8.2.5 <u>Input Power.</u> Propulsive power will be obtained from power rails nominally at 600-volt DC with a variation along the guideway of no more than 10%. The LIMs shall be wound 3-phase normally Y-connected. The maximum phase voltage is 270 volts. During acceleration and deceleration, the power required to the vehicle will vary as shown in Figures 8-1 a, b, c. Since there will be two motors in each vehicle, the power to each will be half the values shown.

8.2.6 Drive Frequency. The motors shall be operated at the frequency at each speed that as close as practical minimizes current.

8.2.7 Ambient Temperature. The LIMs shall provide full performance as specified in Paragraph 3.0 over the ambient temperature range of -45° C to +50°C,

8.2.8 Temperature Protection. Each LIM shall be provided with imbedded temperature sensors to protect against damage due to overheating.

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[19] “The Required Side Gap in the ITNS Chassis.” JEA Book, Task #8. 8.5.

8.2.9 LIM Cooling. By forced air.

8.3 **Thrust Performance**

LIM thrust for the vehicle (two motors) shall meet the requirements shown in Figures 8-1a, b, c unless modified by agreement with client. They are based on the following parameters:

Vehicle Gross Mass	950	Kg
Head Wind	11	m/s
Maximum Rolling Resistance	112	N
Maximum Air Drag	355	N
Peak Acceleration	0.25	g (at half line speed)
Peak Jerk	0.25	g/s
Steady-State Speed	16	m/s
Speed at peak thrust	8	m/s
Duty cycle for peak thrust	<1%	
Acceleration duration	8.5	sec

Based on the above operating conditions, the performance for the two motors are as follows:

Grade	Max Thrust	Thrust @ Max Speed	Min Thrust	Max Power	Power @ Max Speed	Min Power
%	N	N	N	kW	kW	kW
0	2579	461	-2212	26.7	7.4	-18.0
10	3510	1392	-1280	40.2	22.3	-9.2
-10	1647	-471	-3143	14.9	-7.5	-28.9

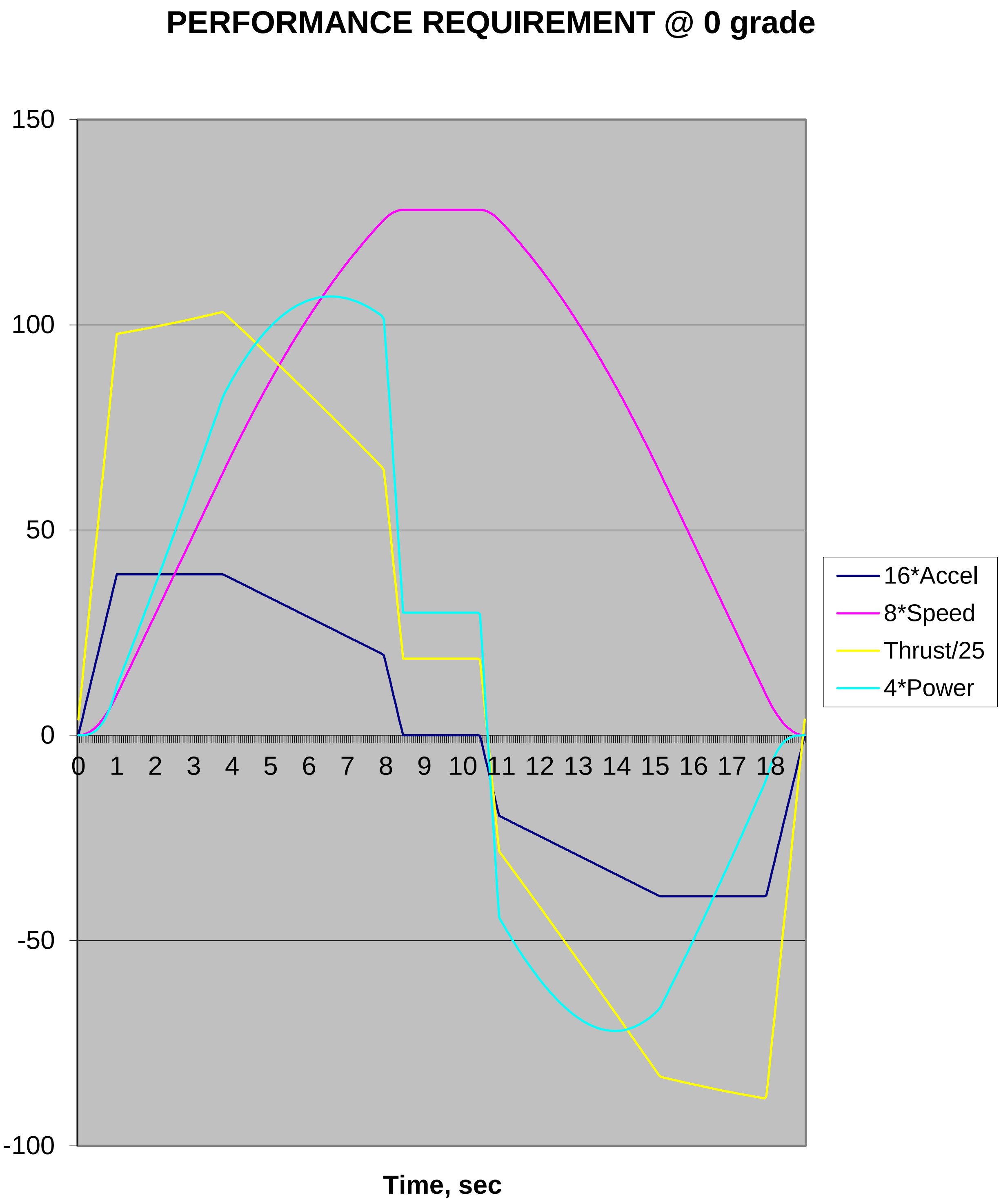

Figure 8-1. Performance Requirement at 0% grade.

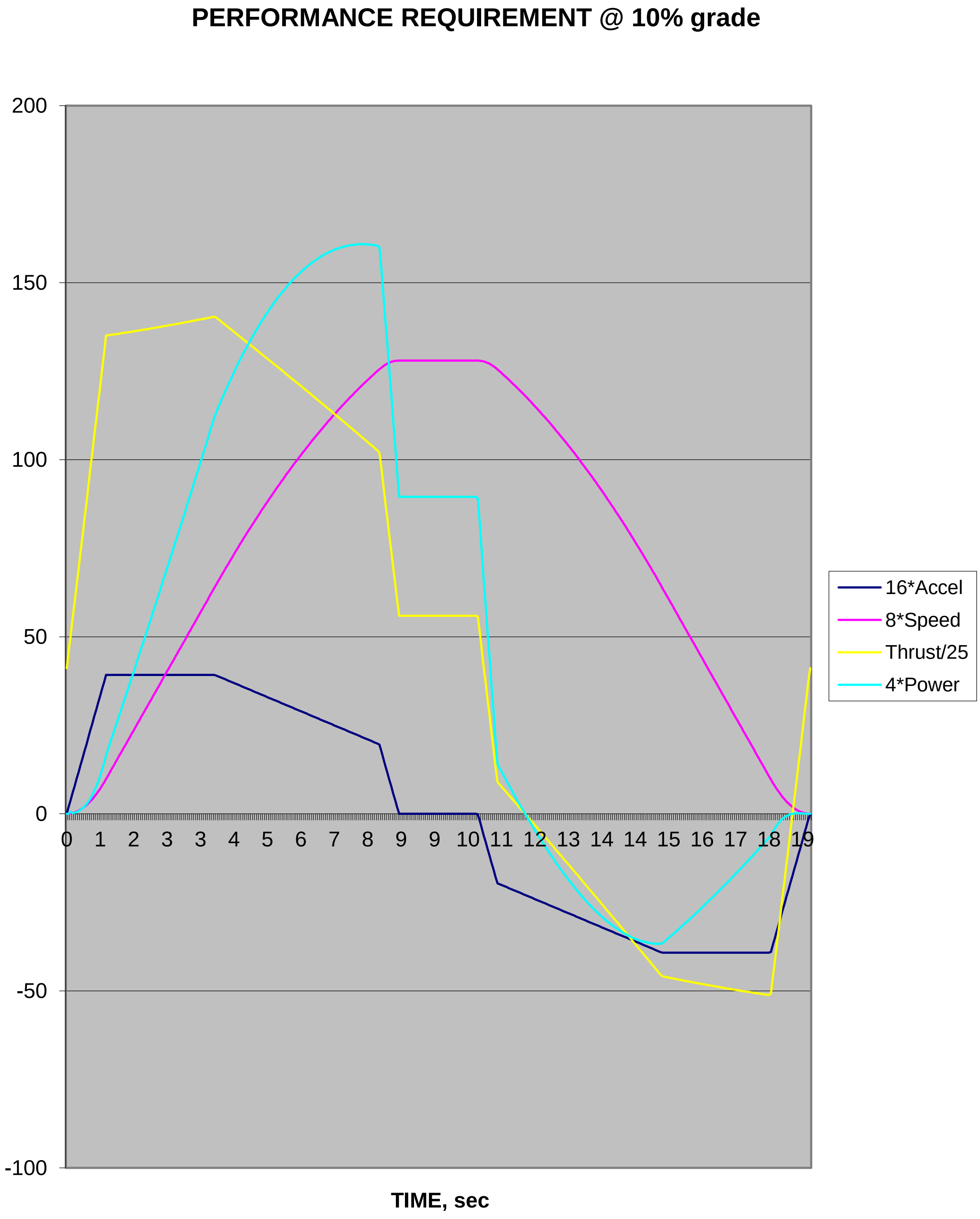

Figure 8-2. Performance Requirement at +10% grade.

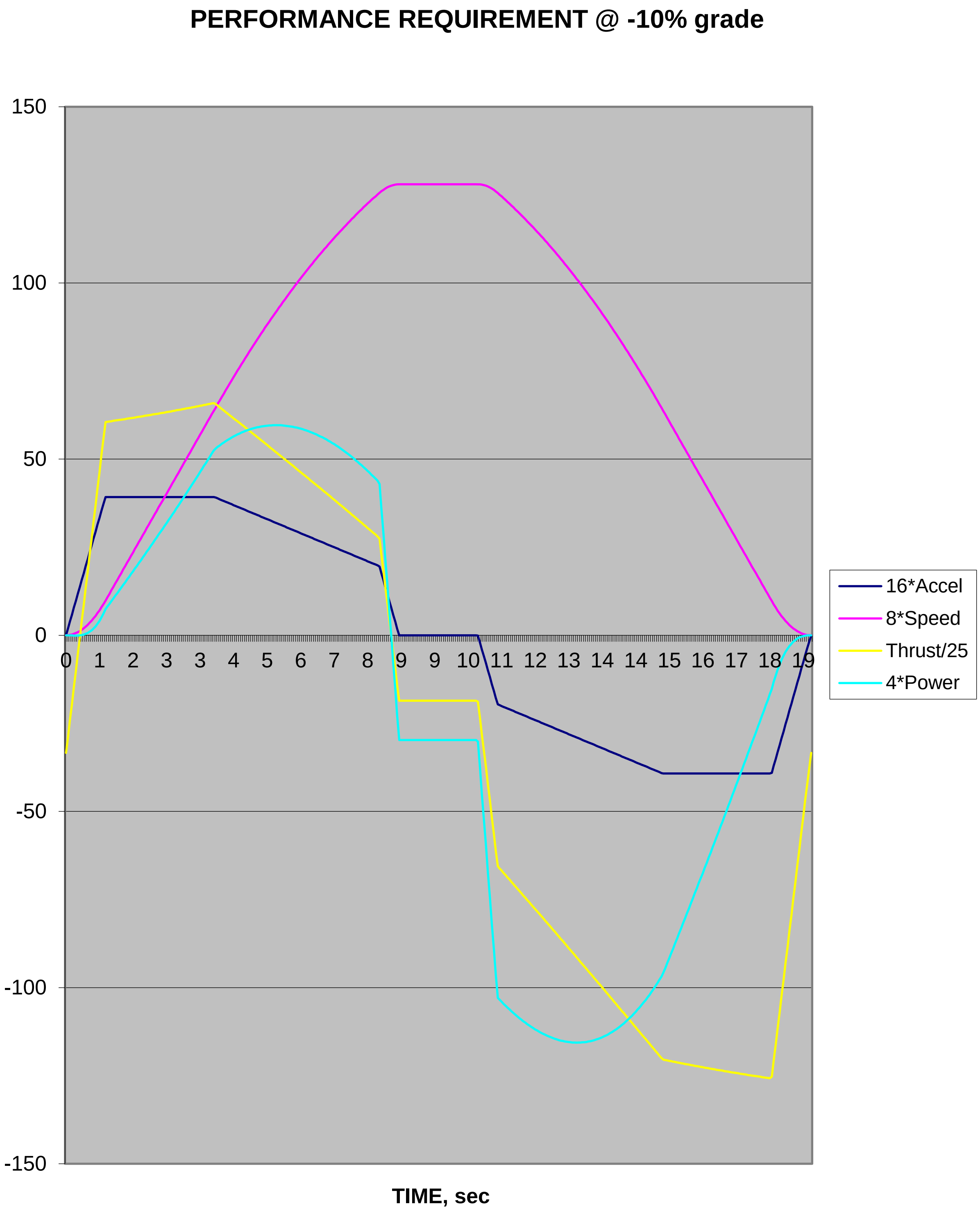

Figure 8-3. Performance Requirement at -10% grade.

9. Wayside Power and Guideway Electrification

This specification is for the design, procurement, and installation of components that will provide power to vehicles on the guideway and to the station, maintenance shop, and test-engineering office of the pilot system.

The requirements are the following:

1. To provide power to the vehicles, utility power shall be converted to nominally 600-volt DC and fed to power rails installed inside the guideway. The maximum power required by a single vehicle is 40 kW so to provide a margin with three vehicles the wayside power conversion equipment shall be designed to handle 100 kW (The three vehicles do not require maximum power all at once). Alternative primary power from solar cells or windmills coupled with power storage means shall be considered.

2. The house power needed for the test-facility buildings shall be determined in consultation with the designer of these facilities.

3. Standard power rails suitable for transit applications at speeds up to 35 mph (56 km/hr) such as manufacture by Insul-8 or Wampfler shall be used. They shall be rated at 300 amps. A small opening in the front face of the insulating rail covering shall allow for the insertion of the power-pickup shoes that ride against the stainless-steel face of the power rail.

4. The guideway feeder cables and the guideway power rails shall be sized to limit the voltage drop to ten percent from nominal to ensure acceptable performance on a vehicle at the end of a guideway sector under heavy load conditions.

5. In the demonstration system, power rails shall be placed only on the outside of the main guideway loop and only on the inside through the station bypass guideway with sufficient overlap at the diverge and merge sections leading into and out of the station so that power can be transferred from one side to the other. Power pickup shoes shall be mounted on both sides of each vehicle. The current to the power-pick up shoes shall be shut off before disengaging.

6. The power-pickup shoes are part of this procurement. They shall be designed to prevent chatter as they engage and disengage at the diverge and merge sections. Tests on disengagement and reengagement were performed at the Insul-8 Omaha facility in 1993-4 during the Raytheon PRT program with satisfactory results.

7. Lightning protection. The vehicles shall be outfitted with lightning protection terminals wired to the on-board ground. This ground shall always be in contact with the ground rail located on the inside wall of the guideway. The ground rails and all metal parts of

the guideway structure shall be periodically bonded and grounded to earth. The lightning protection system shall be designed to carry lightning currents safely away from the passenger compartment of each vehicle to insure safety of the occupants.

8. Safety. The power system design shall insure safety of passengers, operations personnel, emergency personnel, and members of the community. Emergency load-break disconnects shall be available to all personnel requiring access to the guideway. Conductor clearances, insulation, and covering of live parts shall meet Electrical Safety Code requirements.

9. Codes. The system shall be in conformance with the following codes and standards:

    - American National Standards Institute (ANSI)
    - Electronic Industries Association (EIA)
    - Insulated Cable Engineers Association (ICEA)
    - Institute of Electrical and Electronic Engineers (IEEE)
    - National Electrical Code (NEC/NFPA 70)
    - National Electrical Safety Code (NESC)
    - National Electrical Manufacturers Association (NEMA)
    - National Fire Protection Association (NFPA)
    - Underwriters Laboratory (UL)

10. Design and Construction Supervision of the Civil Works

This specification is for the design and construction supervision of the buildings needed for 1) the station platform, 2) a maintenance shop with space and equipment needed to service one vehicle, 3) office space to accommodate the chief test engineer and three associates, and 4) a display and presentation area; for the surveying, design, and construction supervision of the foundations for the posts that support the test-track guideway; and for the required landscaping.

The requirements are the following:

10.1 A station platform at least 5 ft above the ground, 12 ft deep, and 30 ft wide to accommodate three 9-ft vehicles, spaced 1 ft apart, i.e. 10-ft loading berths. The platform shall be open to the elements on the vehicle-loading side, but provided with walls on the other three sides, a roof that covers both the station platform and the parked vehicles, and an entryway for people on the side opposite the positions of the vehicles. There shall be a wall built on the side of the vehicles away from the station platform to prevent people from exiting on the wrong side. The floor will be of durable, non-combustible, exterior-certified material.

10.2 A lateral-transfer table (LTT) shall be placed just upstream of the station platform to permit insertion and removal of one vehicle at a time to and from the station guideway. This device will consist of a pair of parallel guideway sections each 10-ft long with their centerlines 5.5 ft apart. (The centerline of the guideway that bypasses the station is 10 ft from the centerline of the station-bypass guideway.) These guideway sections will be secured to a platform, the LTTP, supported by four flanged rail-type steel wheels perpendicular to the guideway that will ride on a pair of steel rails, with stops at the ends of the rails. In the LTTP's normal position, one of these guideways will be inside the maintenance shop, the floor of which will be at the level of the guideway running surfaces, which are 40" below the station platform. When the vehicle is positioned in the guideway section, the LTTP with the vehicle in place can be pushed laterally until the vehicle is in line with the station guideway. The vehicle can then be pushed into the station area and the LTTP pushed back to its original position. The 10-ft sections of guideway mounted to the lateral-transfer table will be equipped with power rails so that a vehicle can be driven through them under normal wayside power.

10.3 A maintenance shop shall be placed just upstream of the station platform equipped to service one vehicle at a time. The shop is to be equipped with a work bench and appropriate tools and diagnostic equipment. The shop is to be arranged so that a vehicle can be brought in from the outside, wheeled across the shop floor and into the waiting guideway section. While on the shop floor, the vehicle shall be supported by slings from an overhead rail that shall permit the vehicle to be raised to a height suitable for easy work on either side of the chassis. The outside top of the cabin is 100 in above the running surface.

10.4 A test-engineering office shall be designed and built with room for four desks, a blackboard, the wayside computer, and an electronic board that will show the positions of the vehicles. The best position of this office is in front of the maintenance shop to the side away from the guideway. In this way, the maintenance shop and the office can all be under one roof with no necessity for a wall between them. The test-engineering office shall be sufficiently large to accommodate a group of ten visitors and equipped with projection equipment.

10.5 A display and presentation area adequate to accommodate up to a dozen visitors.

10.6 Provision for state-of-the-art fire safety of the buildings shall be provided.

10.7 An accurate survey to locate the positions of the foundations for the posts, which will be nominally 90 ft apart.

10.8 Design and construction supervision of the foundations for a loading condition of a

190,000 ft-lb bending moment at the base of each post.

10.9 Landscaping shall be provided per further instructions.

10.10 Requirements for PRT station and ticketing

1. A PRT station must accommodate all kind of people: regular users, occasional users, visitors who have never used it before; people who use cell phones; people who don't; blind people; deaf people; people in wheelchairs, people using walkers; and perhaps other classifications.

2. People's privacy must be protected in the sense that nothing about using ITNS should reduce the limited privacy that people now retain.

3. People must be able to select the destination in the simplest possible way − by viewing a map of all possible destinations.

4. Having selected the destination, there must be a means for paying the fare. To accommodate all types of people it must be possible to pay the fare on the spot. An alternative would be to be able to purchase a fare card at a convenience store, but for a visitor that is an annoying additional step, and he or she may want to pay for just one trip.

5. Having paid the fare, the potential rider must be able to obtain a receipt that will be used to access a specific vehicle, send the destination to the vehicle computer while standing in front of the selected berth, and cause the door to open.

6. If, upon seeing the vehicle door open, the rider notices that the vehicle has been vandalized, there must be a means of rejecting the vehicle and notifying system personnel.

7. For reasons of security, the station must be equipped with video cameras connected to screens at a control room, there must be a means of alerting control room personnel that they must pay attention to a specific station, and there must be a two-way voice communications system between the control room and either all stations or one specific station.

8. It must not be possible for a patron to walk out onto the guideway.

9. The station must be well lit and have fire-extinguishing equipment.

11. Testing

To certify that ITNS is ready for people-moving applications the following series of tests shall be performed:

1. Component Tests

1.1 Switch Tests

1.1.1 One complete switch assembly will be operated for an equivalent of 10 years of operation. Since the average vehicle will travel about 80,000 miles per year, and there will be an average of about two switch operations per mile, in 10 years, there will be about 1,600,000 switch operations. Assuming one switch operation every 6 seconds (0.5 sec for the operation and 5.5 sec to cool between operations) there can be 600 operations per hour, 14,400 operations per day, or 432,000 operations per month. Hence ten years of switch operation can be accomplished in 3.7 months.

1.1.2 The switch assembly shill be subjected to vibrations in the forcing-frequency range of 4 to 18 Hz to determine that there are no natural frequencies in this range.

1.1.3 One switch arm with wheels attached will undergo fatigue testing. A force cycling between zero and 1000 lb will be applied to one of the arms until either 1,600,000 cycles or failure occurs. The results of this test will be compared with the results of finite-element analysis to corroborate the properties of the switch arm, wheel assembly, and axle, and the bearing.

1.2 Door Assembly Tests

The purpose of this test is to prove the endurance of the door-operating mechanism by operating a complete door assembly in a mock-up cabin at least 400,000 times, which is the estimated number of door cycles in 10 years.

1.3 Guideway tests

1.3.1 U-Frame Strength Test. The purpose of this test is to determine the load applied at the position of the upper-lateral wheels needed to exceed the maximum yield stress at the lower corner of the U-frame and also the load required to break the U-frame. This test will determine the adequacy of the finite-element analysis used to design the U-frame.

1.3.2 Guideway Bending and Twisting. Mount the first 90-ft segment of guideway manufactured on a pair of mock-up post brackets. Subject the guideway segment to a center load to determine if the ratio of deflection to load agrees with the calculated value, and subject it to a center twisting moment to determine if the ratio of twist angle to torque agrees with the calculated value.

1.4 Vehicle-to-Wayside, Wayside-to-Vehicle Communications

The objective of this test is to optimize the vehicle antenna configuration including its spacing with respect to the leaky cable, to establish link parameters, and to measure performance in a realistic electromagnetic noise environment. The test will determine how strong an electromagnetic field is needed to interfere with the zone local area network (ZLAN) and to measure its radiated field strength versus distance for comparison with FCC limits. This test will be performed in the presence of 600-volt DC traction power in the first segment of guideway fabricated. The test will be completed without and with guideway covers.

2. System Tests

2.1 The Test Facility

The general layout of the test facility and the planned test-facility buildings are described Section 10. The guideway will be divided into two control zones, one extending from the merge point out of the station to the point the small curve begins in the northwest corner of the test track, and the other from that point to the merge point out of the station. With this configuration, the function of hand-off from one zone controller to the next can be tested.

The test facility will permit tests of all vehicles operating in the system to determine all-weather performance, reliability, dependability, maintainability, comfort, public reaction, environmental noise, electromagnetic noise, station capacity, wear, and operating costs. The control room will be equipped with data collection instrumentation to support the following functions:

2.1.1 Logging of data on each vehicle for:

- Mileage
- Hours of operation, number of stops, number of door and switch operations
- Tests performed
- Speed profiles, accuracy of speed control
- Acceleration profiles related to ride comfort
- Power input
- Failures, consequences, corrective actions, time of occurrence

2.1.2 Performing tests on vehicles

2.1.3 Recording, storing and analyzing data received by the control room.

2.1.4 Overriding each vehicle control system by the control-room operator. The operator will be able to cause a vehicle to move at a desired speed and to override automatic switching.

2.2 Single-Vehicle Tests and Demonstrations

2.2.1 Control and Communications

2.2.1.1 Speed-profile control. Determine that the vehicle acceleration, deceleration, and jerk rates in moving from rest to constant speed, from constant speed to rest, and from one speed to another are as specified. Measure stopping accuracy at a predetermined point. Repeat the tests for various values of control gain.

2.2.1.2 Control accuracy. Measure the ability of the controller to maintain constant speed in the presence of simulated wind gusts produced by means of a drag brake, and with minimum, average, and maximum vehicle gross weight.

2.2.1.3 Vehicle handoff. Test zone-controller to zone-controller vehicle handoff.

2.2.1.4 Vehicle position and speed measurement. By means of wayside measurements, determine the accuracy of transmitted data on vehicle speed and position as determined by on-board encoders. Because of varying vehicle gross weights, accurate encoder position data requires calibration based on wayside markers as a vehicle moves out of the station. Measure the accuracy of such calibration.

2.2.1.5 Vehicle-wayside communications performance. Measure communications performance of the ZLAN.

2.2.2 Chassis Operation

2.2.2.1 Chassis weight. Record chassis weight before other tests are performed.

2.2.2.2 Drive performance. By accelerating and braking the vehicle on a preprogrammed schedule, determine that the LIM thrust vs. speed, thrust vs. current, transport delay, and power factor are as expected.

2.2.2.3 Coasting tests. Perform coasting tests to determine the air drag and road resistance coefficients on the chassis alone, on the entire vehicle, on straight and curved sections, without and with guideway covers. Formulae for determining the coefficients are derived in the internal paper “Coasting Tests.” JEA Book, Task #11, 11.5.

2.2.2.4 Acceleration efficiency. Determine the energy efficiency in accelerating from rest to cruising speed in terms of the ratio of the energy to overcome inertia, air drag, and road resistance to the electrical energy input. Perform these tests with minimum, average, and maximum vehicle gross weight.

2.2.2.5 Cruise efficiency. Determine the motor and drive efficiencies at various constant speeds up to 16 m/s. The power output is the force required to overcome air drag and road resistance multiplied by vehicle speed. The power input is the electrical power input to the vehicle from the wayside source.

2.2.2.6 Overall efficiency. Determine the electrical power input to one vehicle required to start a vehicle from rest, circle the oval guideway once, and stop again in calm air. Compare with the value calculated using data from the previous tests.

2.2.2.7 Auxiliary brake. Observe operation of the auxiliary brake under automatic control after the vehicle comes to a stop. Determine the force required to push the vehicle with the brake applied. Observe operation of the auxiliary brake with the vehicle at line speed to simulate an emergency stop.

2.2.2.8 Tire performance. The precision of speed measurement depends on the diameter of the tire to which the encoder is mounted. The tire diameter depends on load and wear. Measure tire diameter by recording encoder output under various load conditions. Measure the temperature of the load-bearing and lateral tires after runs to check for overheating. If overheating is excessive, modify the tire specifications and repeat the test. Measure tire wear.

2.2.2.9 LIM gap. Measure the LIM gap as each vehicle moves around the test track. Determine the closest practical gap.

2.2.2.10 Electromagnetic interference. Measure the radiated electromagnetic noise spectrum with and without guideway covers. Measure vulnerability to externally generated EM radiation.

2.2.3 Cabin

2.2.3.1 Cabin weight. Record empty-cabin weight before other tests are performed.

2.2.3.2 Interior environment. Monitor cabin temperature and humidity vs. external temperature and humidity continuously throughout the test program.

2.2.3.3 Acoustical noise. Measure the acoustical noise level in the cabin and at various distances from the guideway. Perform isolation tests to determine sources of noise.

2.2.3.4 Rain test. Subject the cabin to the maximum specified rain and determine the amount of leakage through the door seal.

2.2.3.5 Fire test. Conduct fire tests of the cabin floor in accordance with NFPA-130 specifications and requirements.

2.2.4 Single-Vehicle Tests

2.2.4.1 Acceleration efficiency. Determine the energy efficiency in accelerating from rest to cruising speed in terms of the ratio of the energy to overcome inertia, air drag, and road resistance to the electrical energy input. Perform these tests with minimum, average, and maximum vehicle gross weight.

2.2.4.2 Cruise efficiency. Determine the motor and drive efficiencies at various constant speeds up to 16 m/s. The power output is the force required to overcome air drag and road resistance multiplied by vehicle speed. The power input is the electrical power input to the vehicle from the wayside source.

2.2.4.3 Overall efficiency. Determine the electrical power input to one vehicle required to start a vehicle from rest, circle the oval guideway once, and stop again in calm air. Compare with the value calculated using data from the previous tests.

2.2.4.4 Auxiliary brake. Observe operation of the auxiliary brake under automatic control after the vehicle comes to a stop. Determine the force required to push the vehicle with the brake applied. Observe operation of the auxiliary brake with the vehicle at line speed to simulate an emergency stop.

2.2.4.5 Tire performance. The precision of speed measurement depends on the diameter of the tire to which the encoder is mounted. The tire diameter depends on load and wear. Measure tire diameter by recording encoder output under various load conditions. Measure the temperature of the load-bearing and lateral tires after runs to check for overheating. If overheating is excessive, modify the tire specifications and repeat the test. Measure tire wear.

2.2.4.6 LIM gap. Measure the LIM gap as each vehicle moves around the test track. Determine the closest practical gap.

2.2.4.7 Electromagnetic interference. Measure the radiated electromagnetic noise spectrum with and without guideway covers. Measure vulnerability to externally generated EM radiation.

2.3 Multiple Vehicle Tests and Demonstrations

2.3.1 System Tests

2.3.1.1 Normal operation. As more than one vehicle becomes certified through the Single-Vehicle Test Program, and between single-vehicle certification tests, operate multiple vehicles as in normal service, first with sand bags representing passenger weight and then with passengers aboard.

2.3.1.2 Station flow. Demonstrate vehicle flow through a station and compare with simulation results. Through a station each vehicle follows the commands: Move forward if possible if in the input queue or if in the station with no destination if no passengers are approaching the vehicle. Otherwise wait in the station until a station destination is received and the door is closed. Move to line speed on command from the station zone controller (SZC). Test these operations. Determine that one vehicle stops behind another at the predetermined tolerance.

2.3.1.3 Ride comfort. Determine the acceptance of the ride comfort by obtaining the opinions of passengers of various ages and conditions who have ridden in a vehicle on the test track at various speeds up to the design maximum. Determine in this way if the values of comfort acceleration, jerk, roll rate, and bank angle to which the test track was designed need to be modified.

2.3.1.4 Inclement weather operation. Conduct tests with and without passengers during wind, snow, rain and ice storms. Determine if performance is as required and recommend changes if necessary. Particularly, determine if snow removal methods envisioned are adequate or if changes are needed. Command changes in line speed as required under high-wind conditions and observe the behavior of the vehicles as they slow down and later resume normal speed.

2.3.1.5 Vehicle merging. Demonstrate vehicle merging and compare with merge simulations. Test the operation of vehicles leaving the station and merging with vehicles on the main line at minimum headway.

2.3.1.6 Reliability testing. Run one or more vehicles continuously to determine failure rates of various components. First with sandbags representing passengers, operate the vehicles at closer and closer headways and determine the accuracy and reliability of the inter-vehicle spacing.

2.3.2 Vehicle Tests

2.3.2.1 Vehicle pushing. Demonstrate a vehicle soft engaging and pushing a vehicle ahead into a station, operating the auxiliary brake and switch remotely via a wireless connection to an operator.

2.3.2.2 Rear-end collision. Cause one vehicle to run into the rear of another at speeds up to the rated speed for the shock-absorbing bumper. Measure vehicle accelerations and critical-point stresses and compare with calculated performance.

2.3.2.3 Power interruption, voltage transients and spikes. Test operation with simulated electrical disturbances including power cutoff. Observe operation of the system as it slows down and then restarts.

2.4 Station Functional Tests

2.4.1 Operational Demonstration. Demonstrate station entry and exit by passengers, passenger flow, passenger adaptability, ticket reading and destination programming, vehicle-door control, and vehicle entry and exit by passengers. Obtain data on passenger opinions of the operation.

2.4.2 Check stanchions for ease of use, environmental resistance and function.

2.4.3 Check general station arrangement for ease of use and accessibility.

2.4.4 Check station design and materials for ease of maintenance.

2.5 Central-Control Testing

Demonstrate basic connectivity between wayside zone controllers and central control. Through simulations of multi-station networks, demonstrate central-control operations of data collection, system speed, empty-vehicle movement, and traffic control.

2.6 Fail-Safe, Fault-Tolerant, Failure-Management Tests and Demonstrations

Automatic fail-safe and fault-tolerant mechanisms and failure-management procedures have been designed into the system to detect and respond to anomalies and failure conditions to minimize the risk of personal injury, personal delay, and property damage. Induce failures into the system to determine the system's response to failures in the following areas:

ONBOARD

- ZLAN communications
- Position encoding
- Auxiliary braking
- Vehicle computer
- Collision
- Marker detection and decoding
- Thruster
- Vehicle switching
- Traction power
- Battery and low-voltage power supply

WAYSIDE

- ZLAN communications
- Wayside computers
- Wayside-to-wayside communications
- Vehicle log in
- Central computer
- Wayside-to-central communications

2.7 Operations & Supportability Demonstrations

2.7.1 Reliability & Safety

Establish and maintain a daily failure log and computerized data files, and perform the following analyses:

- Compare actual reliability with system-engineering allocations and predictions.

- Determine component modifications for production models.

- Determine causes and effects of failures and prescribe corrective actions.

2.7.2 Environmental

Establish and maintain a daily weather log and computerized data files. Analyze the effects of water on the operation of the system during the single- and multiple-vehicle tests and demonstrations.

2.7.3 Maintenance, Maintainability, & Supportability

Establish and maintain an equipment maintenance log and computerized data files and perform the following analyses:

- Compare actual maintainability with system-engineering allocations and predictions.
- Establish design criteria for all maintenance-support equipment.
- Refine estimates of operating and maintenance costs.

12. Site Planning and Network Layout

This section presents, *inter alia*, information needed to initiate a study of an application of ITNS in a specific setting and some of the differences in comparison with conventional transit planning.

Before initiating a serious study, a preliminary analysis of the problem should be made to obtain a feeling for the potential financial feasibility of the project. A preliminary analysis contains the basic elements of a detailed study, and is intended to obtain an initial feeling for the financial feasibility of an installation before going into serious detail. The steps are the following:

- Expected Trip Origins and Destinations
- System Layout
- Ridership Estimate
- Cost Estimate
- Financial Feasibility
- Architectural Renderings

12.1 Expected Trip Origins and Destinations

The first step in a study aimed at determining whether ITNS will be feasible is to determine where people will be coming from and where they will wish to go. The characteristics of ITNS are such that the existence of the system is likely to have a strong influence on the travel patterns, so the process is iterative. The needed information is both the geographical pattern of origins and destinations and the numbers of people wishing to travel, both in the peak period and on a daily, weekly, and yearly basis.

12.2 System Layout

The first layout is the first tentative plan of line and station locations based on the expected trip origins and destinations. The layout of a development project is influenced by the type of transit that can be counted on as an alternative. The personal rapid transit concept provides great flexibility in layout compared with conventional rail systems for three basic reasons:

1) The required right of way is much narrower—going from a 38-foot strip for a necessarily two-way LRT alignment to land needed only for posts two feet in diameter at the base typically 90 ft apart; and stations, the smallest of which need have a foot print of only about 28 feet along the alignment by 7 feet wide.

2) While the newer LRT systems are virtually always deployed as a single two-way line, the in vehicle switching system and low cost of PRT permits much greater flexibility. PRT could be in the same alignment or it can, more profitably, be deployed in networks of one-way lines, thus at least doubling accessibility for the same cost.

3) Since PRT stations are all on bypass tracks off the main line, adding a station does not reduce the average speed between stations as it necessarily does in a conventional system, where, if one car must stop, all others behind it must stop.

The analogy to PRT is, except for width, the freeway, where one doesn't have to slow down on-line to get off. With respect to width, one PRT line three feet wide has the same capacity as three freeway lanes 48 feet wide, a reduction of 12:1 in the land that must be set aside for transportation, yet the PRT system requires land only for the posts and stations.

With on-line stations, as required in LRT, modern planners tend to place the stations at least a mile apart to increase the average speed to a range competitive with the automobile. With off-line stations, it is possible to have, if it makes economic sense, as many as six or eight stations per mile. In LRT, one can have speed at the sacrifice of accessibility or accessibility at the sacrifice of speed. In PRT one has both speed and accessibility.

"Principles of Network Layout," beginning on page 69, is required to develop a layout. A preliminary layout can be suggested if given the necessary information: a plan of the development indicating the expected amount of travel between points.

12.3 Ridership

Detailed ridership analysis requires the services of a specialist, and may be quite expensive because much data must be gathered. Preliminary estimates are, however, always necessary. The "modal split" or fraction of vehicle trips taken by transit is influenced by planning decisions such as the layout of roads, the ease of parking, and the cost of parking. If the planning decisions are given, the population density, and the locations of residential areas, shopping centers, office parks, etc. a preliminary estimate of the probable amount of travel and can be developed and thus a "ball-park" feeling for economic viability.

12.4 Cost Estimate

The above information is enough to use available data to arrive at a preliminary cost estimate. Costs will come down as production quantity increases, so a cost estimate must be made in view of a probable total production quantity at the time the system would be ordered.

12.5 Financial Feasibility

A 20-story building would not be financially feasible without elevators. For some people, a stairway is an alternative to an elevator, but for most people there is no alternative to an elevator. A newly planned community may be designed completely around the automobile, as most have been. It is an alternative, but it comes at a price because of the very large fraction of land that the automobile system requires and because of unavoidable congestion resulting from slow movement because automobiles must stop at cross streets and wait for others to pass. The bus is considered an alternative, but its inherent service concept causes a typical bus trip to be about three times as long as a typical auto trip. Conventional rail systems and the large-vehicle automated people movers require daytime population densities much higher than most modern developers would like, and if placed in developments of moderate density often produce shockingly high costs per passenger mile.

PRT, on the other hand, drastically cuts land use, increases average speed and reduces energy consumption by factors between two and three, provides much increased accessibility over on-line-station rail systems, can recover most, if not all its costs, and provides an unparalleled level of service for both people movement and goods movement. PRT does this while virtually eliminating noise and air pollution. By powering from wayside batteries charged at night, PRT need not add to the peak utility load.

Determination of its full financial benefit, therefore, requires a comprehensive comparison of the whole planned community with PRT included and without. Fortunately, we find that the financial feasibility of PRT quite often does not require any such elaborate study, however valuable it will be. In many developments, financial feasibility can be determined simply by offsetting its cost against the cost of parking structures that wouldn't have to be built, or in savings of the multiple of parking spaces the auto system requires. In any case, a financial feasibility study should start with a several-hour conversation between the PRT planners and the developer to determine in some detail what is driving the cost of the development.

12.6 Architectural Renderings

Visual impact is always an important consideration. Therefore, to get a preliminary feeling for the appearance of a PRT system, several architectural renderings of the system in critical locations are needed.

12.7 Principles of Network Layout

All the important parameters involved with network layout depend on line speed. Kinetic energy, air drag, curve radius, and stopping distance all depend on the square of speed. The power to overcome air drag increases as the cube of speed; and, with given guideway roughness, however small it may be, the suspension required is more demanding as speed increases. The system will therefore become more expensive as line speed increases, and this must be balanced against the expected increase in ridership as the average trip speed increases. The bottom line is that the planner needs to know how line speed affects cost per passenger-mile. An iterative process, initially based on experience and judgment, is required to determine the optimum line speed.

The minimum curve radius at the desired operating speed depends on ride comfort. The minimum right-of-way width of a pair of cross streets that can accommodate a PRT system is 30% of the minimum curve radius. With all passengers seated, as is the case in PRT, the maximum acceptable lateral acceleration is $A_{max} = 0.20g$, and the minimum radius of a flat curve is $R_{min} = V^2/A_{max}$, where V is the speed in the curve. If the curve is superelevated, i.e., banked, R_{min} is 65% as much.

The minimum distance between branch points is the sum of two distances: the distance the vehicle moves at line speed during the 0.4-sec switch throw time, plus the stopping distance with a 0.5g emergency-braking rate. This distance is $V(0.4 + V/g)$.

The lengths of the off-line station guideways depend on line speed and the required number of berths. Data are available to determine these lengths.

Within these restrictions, guideways of any configuration can be deployed; however, certain configurations are better than others. Optimum design of a PRT networks is an art. The following need to be considered:

- *Y interchanges vs. multilevel interchanges.* Multilevel interchanges may be necessary for very high capacity, but produce greater visual impact at any one point. It is best to try to lay out a network using Y interchanges and to use multilevel interchanges only if or where necessary. Y interchanges have the disadvantage that vehicles must merge before they diverge, thus creating bottlenecks, which can be relieved by using the higher-impact multilevel interchange. Fortunately, in a great variety of applications, the network can be laid out so that the capacity is adequate with Y interchanges. Y interchanges are more of a challenge for the control system, but the problems have been solved.

- *One-way vs. two-way lines.* With one-way lines, twice as much land area can be put within walking distance of stations for the same total track length. Moreover, the interchanges are simple and visual impact at any one location is minimized. One-way lines have the disadvantage of more circuity, where circuity is defined as the ratio of the trip length on the network between a pair of stations divided by the direct-line distance. Building the network out of a series of modest-sized loops will minimize circuity. Since the trip time on a PRT system is very short compared to the total trip time counting walking, the effect of increased circuity on ridership can, by careful design, be made so small that the cost per passenger-mile is lower with the one-way configuration. There is, however, no reason to constrain a PRT system to one-way networks in the way that conventional transit systems, by their nature, must be deployed in two-way configurations; but, to eliminate vehicle-to-vehicle transfers, two-way systems require complex interchanges.

- To maximize system capacity, networks should be laid out wherever possible with merges and diverges alternating, thus relieving potential bottlenecks. The example on the following page has merges and diverges alternating. In developing such a network, it is useful to think of the guideways as rubber bands of the right topology and ready to fit any street pattern.

- Because curved track costs more than straight track, curves should be kept to a minimum.

- A PRT system is not restricted to being elevated. Positioning above ground, at ground level or underground is a planner's decision. The off-line guideways to the stations of an elevated system may be brought close to the ground so that a stairway and elevator would not be needed, but at the cost of a longer off-line guideway and the need to fence off an area on both sides of the station.

- A small ITNS network is illustrated in Figure 12-1.

12.8 Marketing

The purpose of the demonstration or pilot program is to develop and provide the information needed to secure orders for ITNS. This task will prepare marketing materials: a comprehensive brochure, a realistic virtual-reality simulation of the operation ITNS in a real setting, and a suitable marketing presentation. The personnel involved will be trained in the use of the simulation, will become informed in all aspects of the system that will be questioned by consulting engineers and planners at specific sites, will conduct site visits, and will secure at least one order for the first operating system. Funds to secure subsequent orders will come from the proceeds of earlier orders.

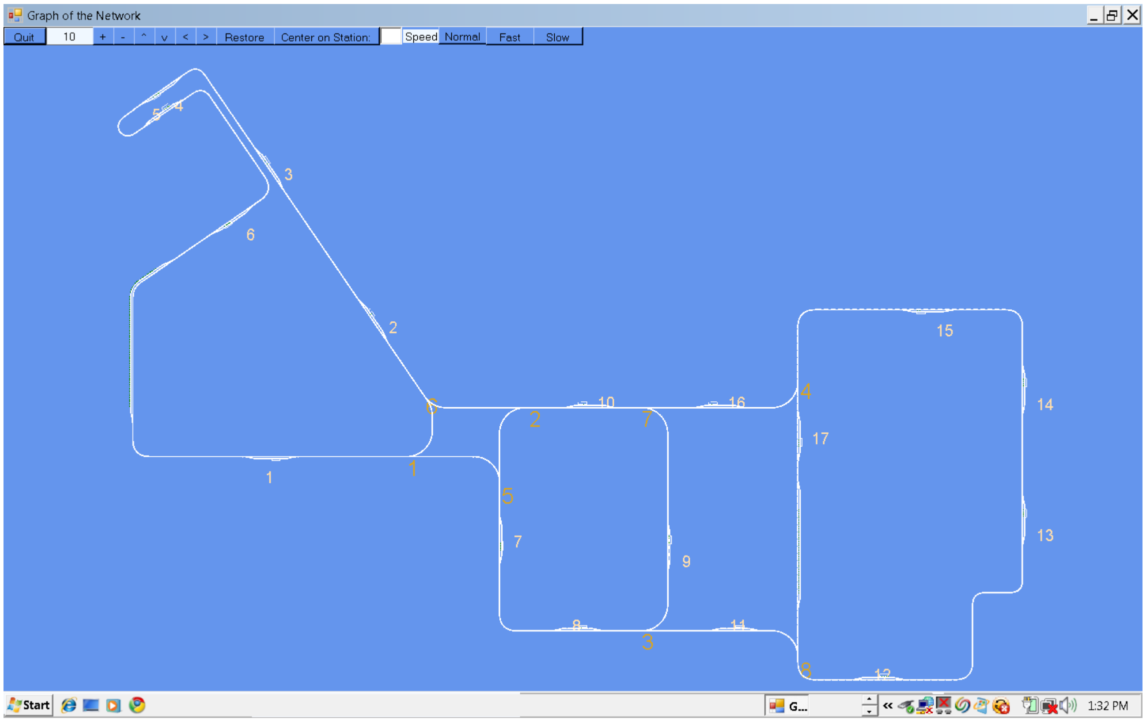

Figure 12-1. A PRT network with Y-interchanges only and with alternating merges and diverges.