

Control of Personal Rapid Transit Systems

J. Edward Anderson

The problem of precise longitudinal control of vehicles so that they follow predetermined time-varying speeds and positions has been solved. To control vehicles to the required close headway of at least 0.5 sec, the control philosophy is different from but no less rigorous than that of railroad practice. The preferred control strategy is one that could be called an "asynchronous point follower." Such a strategy requires no clock synchronization, is flexible in all unusual conditions, permits the maximum possible throughput, requires a minimum of maneuvering and uses a minimum of software. Since wayside zone controllers have in their memory exactly the same maneuver equations as the on-board computers, accurate safety monitoring is practical. The paper discusses the functions of vehicle control; the control of station, merge, and diverge zones; and central control.

Introduction

The problem of closed-loop automatic longitudinal control of a single vehicle constrained to follow a guideway at a specified time-varying speed and position within adequate accuracy has been solved by several investigators [Garrard, Caudill, Kornhauser, MacKinnon, and Brown, 1978; Lang and Freitag, 1978], and analytical equations for the required speed and position gains have been derived [Anderson, 1997]. The architecture of checked redundant microprocessor control for automated transit vehicles has been developed and has been shown to be able to achieve a safety record as good or better than a modern rapid rail system [Milnor, and Washington, 1984]. The major challenge in PRT control has been to control a large fleet of vehicles operating at fractional-second headway and merging and diverging in and out of stations and between separate branches in a network of guideways with an acceptable level of safety, comfort, and dependability, while meeting other essential criteria. A great deal of work has been done on this problem over the past few decades. Much of the published work can be found in conference proceedings [Anderson, 1974; Gary, Garrard, and Kornhauser, 1976; Korn-

hauser, 1978; Mahan, Tucker, and Grasso, 1978], and in results of the Urban Mass Transportation Administration's Advanced Group Rapid Transit Program [Womack, 1979; Greve, Haberman, and Lang, 1985]. While the AGRT system was designed for 3-sec headway, much of the work is directly applicable to PRT. Together with the work of The Aerospace Corporation PRT Program [Irving, Bernstein, Olson, and Buyan, 1978] and the DEMAG + MBB Cabintaxi PRT Program [Hobbs, Heckelmann, Patt, and Hill, 1977], one can obtain an excellent perspective on the field.

In a short paper, it is not possible to describe any appreciable portion of this work; however, it is more useful to give a synthesis of conclusions reached concerning the means of controlling a PRT system, which have been built on the shoulders of prior investigators. I first discuss the criteria any PRT control system must meet. Then, it is necessary to discuss the problem of safe achievement of adequately low time headway between vehicles and how the safety philosophy must differ from standard railroad practice. Next is a discussion of strategies of control of many vehicles in a network. With this background, the next topics are the information that must be available on board the vehicles and at various wayside points, the sensing and communication requirements, and the mathematics involved. I do not discuss lateral control because, in most PRT systems, it is achieved passively by wheels running against lateral surfaces.

Control Criteria

Line and Station Throughput.

Analysis of PRT networks in many applications has shown that fractional-second headways are both needed and attainable. The 1974 UMTA Administrator Frank Herringer, in testimony before a committee of the Congress of the United States, said: "A DOT program leading to the development of a short, one-half to one-second headway, high-capacity PRT system will be initiated in fiscal year 1974." [Herringer, 1974] This statement was a result of consensus among workers in the PRT field in consultation with the Research and Development staff of UMTA on the need and practicality of headways as low as 0.5 sec. Offline stations must be designed to meet expected input and output flows, and the system must be designed to prevent excessive congestion at merge points and destination stations.

Safety

A PRT system must provide a level of safety in terms of injuries per 100 million miles at least as good as a modern rapid rail system, and preferably better—better because the improvements provided by PRT in all areas must be good enough to justify the development cost. To achieve this level of safety, the on-board and wayside computers must be checked redundant.

Dependability

The term "dependability" is less often used than "availability," which is measurable in conventional transit systems as the percentage of trains that arrive at stations when expected. Dependability is the ratio of person-hours not delayed due to failures to the number of person-hours of operation. It is a more meaningful criteria and, in PRT, can easily be measured and updated trip by trip by a central computer [Anderson, 1992]. In a recent PRT program I was involved with, it was specified that the undependability (1 - dependability) should be no more than 3 person-hrs of delay per 1000 person-hrs of operation. From our analysis, if the safety criterion is met, the undependability will be at least an order of magnitude less.

Ride Comfort

Longitudinal maneuvers must be performed in such a way that International Standards Organization ride comfort standards on acceleration as a function of frequency are met. As to maneuvers, the most recent federal standards on ride comfort that would be applicable to vehicles in which all passengers are seated were set by the National Maglev Initiative Office. They restrict acceleration to 0.2 g and jerk to 0.25 g/s in normal operation. The maximum emergency-braking deceleration depends on whether or not passenger constraints are provided. If not, the criterion must be that the passenger not slide off the seat in an emergency stop.

Changing Conditions.

The control system must be able to reduce cruising speed in high winds and must be able to cope with any unusual situation, such as a stopped vehicle, that would require vehicles to slow down or stop away from a station.

Dead-Vehicle Detection

There must be a means to detect a dead vehicle on the guideway, however remote that possibility may be. Each vehicle must transmit its speed and position at frequent intervals to a wayside computer—a zone controller. If the zone controller suddenly does not receive the expected signal, it must be programmed to remove the speed signal for all vehicles in that link and transmit this information to the next upstream zone controller. Each vehicle's control system is configured to command reduction in speed to a creep speed if the zone controller's speed signal is not received. A finite creep speed permits vehicles ahead of the failed vehicle to move safely to the next zone, it reduces anxiety, and with seated passengers is safe. Magnetic detectors are placed at specified intervals along the guideway to inform the zone controller of passage

of a vehicle. Thus, if a vehicle passes one of these markers and not the next, the location of the dead vehicle is approximately known. Then, because the passengers are seated and can be protected, and the vehicle can be protected by appropriately designed shock-absorbing bumpers [Anderson, 1994], a creeping vehicle can be permitted to advance until it soft engages with the dead vehicle, whereupon the position of the dead vehicle becomes known and an appropriate failure strategy can be engaged.

Interchange Flexibility

The simplest interchange is a Y, with either two lines entering and one exiting or vice versa. Such an interchange gives the least visual impact at any one point, but it requires that vehicles first merge, then diverge, which creates a bottleneck after a merge. Desiring to obtain maximum possible throughput, The Aerospace Corporation used two-in, two-out, multilevel interchanges, which permit vehicles to diverge first and then merge. With such interchanges, the input and output capacity of the lines is the same, hence the worst that can happen is that a vehicle may have to be diverted from the direction it would normally go. Thus the control system does not have to be concerned with sending too much traffic along a particular line. If Y-interchanges are used, control is more complex and is discussed below. Since Y-interchanges are often necessary, the control system must permit them.

Vandalism and Sabotage

A system in which the control functions are distributed and the wayside computers are protected, for example in safe rooms under the stations, will be less susceptible to damage than a system in which a central computer plays an essential role. To minimize the consequences of failures of any kind, distributed control is preferred. The required central-computer functions should be such that the worst that can happen if it fails is that the system will operate less efficiently.

Modularity

The control units should be easily exchangeable so that down time is minimized.

Expandability

The control system should be designed for easy expansion of the system.

Principles of Safe, High-Capacity PRT

The Headway Equation

The minimum safe spacing between vehicles is the longest emergency stopping distance minus the shortest failure stopping distance. It is given by the equation

$$H_{\min} = Vt_c + \frac{V^2}{2} \left(\frac{1}{A_e} - \frac{1}{A_f} \right) \quad (1)$$

in which V is the line speed, t_c is the time constant for brake actuation, A_e is the minimum emergency braking deceleration, and A_f is the maximum failure deceleration. Strictly speaking there should be a term added involving the rates of change of deceleration (jerk), but the emergency jerk can be made high enough so that jerk does not add to H_{\min} . If L is the length of the vehicle, the minimum time headway, using equation (1), is

$$T_{\min} = \frac{L + H_{\min}}{V} = \frac{L}{V} + t_c + \frac{V}{2} \left(\frac{1}{A_e} - \frac{1}{A_f} \right) \quad (2)$$

Equation (2) shows first that PRT vehicles should be as short as possible. With careful design, a length of 2.6 m is practical. A typical operating speed is 13 m/s, in which case the first of the four terms in T_{\min} is 0.2 sec. Boeing work [Nishinaga and Colson, 1983] showed that vehicles can transmit their speeds and positions as frequently as once every 40 msec. To command emergency braking requires two such transmissions. The braking time constant, once a signal is received must be very short. With the right technology, 100 msec is practical. Therefore, with some extra allowance, assume $t_c = 0.2$ sec. If the minimum line headway is to be 0.5 sec, the bracketed term in equation (2) can thus be no more than 0.1 sec—practically zero. This means that *in a fractional-second-headway PRT system, the design must be such that the minimum emergency deceleration must be as high as the maximum reasonably possible failure deceleration.*

The most recent indication of the practicality of close-headway control is an announcement by the National Automated Highway System Consortium [Holusha, 1996] that in 1997 "10 specially outfitted Buick LeSabres will take part in the first test of an automated highway." A companion article on the same page says that these 200-inch long autos will operate at a spacing of only 6 feet at "50-plus miles an hour." This works out to a time headway of 0.309

sec. At 30 mph the headway would be 0.515 sec.

Departures from Railroad Practice

In railroad practice, trains may be so long that the first term in equation (2) may be several times the term $V/2A_e$. Also, at grade level, it is easiest for some foreign object or another train to quite suddenly appear ahead. In the worst case the train ahead theoretically stops instantly, in which case the fourth term in equation (2) is zero. Relative to the size of the term L/V , this is not a severe assumption and is conservative. In railroad practice it is standard to design for the so-called "brick-wall" stop in which A_f is infinite.

A railroad block-control system depends in emergency situations on a vital relay that virtually never fails. Its failure is likely to cause a collision, but such a failure is so rare that it is assumed never to occur. What is implied is that the probability that the vital relay fails when it is needed is so low that it is acceptable. There is no other choice. *In any moving system the simultaneous occurrence of two very improbable major failures may set up the conditions for a collision.*

In railroad practice the philosophy is that if one train is to stop instantaneously, the train behind must be able to stop in a short enough distance to avoid a collision. In PRT, the philosophy must and can be that if one vehicle stops instantaneously, someone is already killed. Therefore, one must and can design the system so that, barring a calamitous external event, it is "impossible" for one vehicle to stop instantaneously. Just as in railroad practice, "impossible" has the meaning stated in the paragraph above.

This failure philosophy requires careful analysis of every circumstance in which a sudden stop could theoretically occur. There are only two: 1) Something falls off a vehicle or a foreign object appears that wedges the vehicle in the guideway and causes it to stop very quickly, and 2) a collision with the junction point of a diverge. Making the first of these possibilities acceptably remote requires careful design and an inspection procedure that frequently assures that nothing is coming loose. Experience with road vehicles gives a feeling for the possible frequency of such an occurrence, which almost never happens to a well maintained vehicle. By more detailed analysis than possible here it can be shown that by proper design a diverge collision will require two simultaneous highly improbable failures plus a rare "Act of God" event.

If there are many vehicles on a guideway, there are two additional possibilities for a sudden stop. One is a runaway vehicle entering a station and failing to stop before colliding with a standing vehicle, and the other is a merge collision. By use of checked-redundant vehicle control, such as developed by Boeing, it is practical to design the control system in such a way that the mean time between over-speed failures continuing to a station collision is at least a million years. It can be shown that a merge collision would require two such failures in very close proximity in space and time, which places its

MTBF in a range more remote than the estimated life of the universe.

In a PRT system designed as indicated above, there are no sudden stops; however, there may be on-board failures that require emergency braking. Equation (2) shows that to achieve safe fractional-second headway, one vehicle cannot be permitted to stop quicker than the vehicle behind. This requires closely controlled, constant-deceleration braking regardless of the condition of the guideway, which rules out systems that rely on braking through wheels because in rainy or snowy weather the coefficient of friction may vary along the guideway. This is the safety-related argument for the use of linear electric motors. Another important reason for use of linear electric motors (with an appropriate guideway design) is to eliminate the need for guideway heating and to permit the use of low-friction running surfaces. It may be noted that it is quite likely best to decelerate at the normal rate if an on-board failure is detected. Trying to decelerate too rapidly may cause more problems than it solves.

The final factor in the difference between PRT and railroad practice is that PRT vehicles are light enough so that reasonably sized bumpers can absorb a great deal if not all of the collision energy, and all passengers are seated. By using data from auto safety practice, a PRT vehicle therefore can and should be designed so that even a collision need not cause injuries [Anderson, 1994].

Control Strategy

General Considerations

Adequately tight control of the speed profile can be attained by using proportional-plus-integral (P+I) control based on tachometer feedback. A vehicle must be able to perform any one of the following maneuvers:

- Speed change from given speed and acceleration to new speed.
- Slip given distance forward or backward from line speed.
- Slip given distance from acceleration maneuver.
- Slip given distance from slip maneuver.
- Advance given distance in station from rest or from deceleration maneuver.
- Emergency stop.

Code must be written so that the time-varying speed and position profiles of any of these maneuvers with any set of desired parameters can be calculated in the on-board computer and used as commands to the controller. If during each computational or time-multiplexing interval a wayside zone controller transmits a speed signal to all vehicles in its domain and at certain command points can transmit to a specific vehicle a maneuver command with a parameter (the

desired speed, distance to slip, etc.), the vehicle has all the information it needs to perform the maneuver. Moreover, by calculating the speed profile in parallel, the zone controller has all of the information it needs to monitor the execution of the maneuver. If a vehicle moving at line speed moves away from the desired time-varying position, the integral portion of the P+I controller corrects the position. If the tachometer drifts, as it will, magnetic markers along the guideway provide the basis for correcting the tachometer constant. If the speed of a vehicle at a certain time is in error in excess of a preset amount, the zone controller assumes a fault and removes the speed signal from its domain. The vehicle controller is programmed to command creep speed if it does not receive the speed signal, so any failure, even at merges, causes a safe reaction.

We now have a system in which the vehicles each closely and reliably follow commanded speed profiles and are simultaneously monitored for failures by wayside zone controllers. On this basis it is possible to describe the maneuvers needed to operate the system. This discussion is based on extensive experience with a comprehensive PRT-network simulation. We first consider the progress of an occupied vehicle from the point a passenger group enters to the point that they arrive at their destination, then we consider movement of empty vehicles.

Movement of an Occupied Vehicle.

Let's join a group traveling together to the same destination by choice. We either have a magnetically coded ticket with the destination recorded on it because we take the same trip every day, or we must approach a ticket machine to punch in a destination, pay a fare, and receive a ticket. With a valid ticket we approach the forward-most available vehicle in a line of vehicles and insert the ticket into a stanchion in front of the stopped-and-ready vehicle. This action flashes the origin and destination station to a central computer which has in its memory the estimated arrival times of all vehicles moving through the system. If our vehicle is expected to arrive at its destination station at a time when the station is full and cannot receive another vehicle, we are informed that we must wait a specified time before we can try again. Generally this will be a very small time and the central computer will prioritize the unfulfilled demands for service.

When the ticket can be accepted, the station computer so informs us, unlocks our vehicle's door, and transfers the memory of the destination to the on-board computer. We enter our vehicle, sit down and when ready one of us closes the door. Thereupon the door is automatically locked. If our vehicle is not in the forward-most loading berth, it must wait until the vehicle or vehicles ahead move out. If it cannot yet be commanded to line speed because an opening is not yet available, it is commanded to advance as far forward as possible.

The station zone controller meanwhile is examining the flow passing the station for an opening. The vehicles on the main line maintain separations at or greater than the minimum separation permitted by equation (1). Note that there need at this point be no synchronization. If there is no traffic on the main line a vehicle can be commanded to accelerate to line speed at any time it is ready. As traffic on the main line builds up, say with the approach of the morning rush hour, vehicles pass stations at any spacing down to the minimum allowed.

To create an opening for our vehicle, the moment the zone controller commands our vehicle to line speed it may command a mainline vehicle too close ahead to slip ahead if possible and a mainline vehicle too close behind to slip back. If slipping of the mainline vehicle back would cause the headway between it and the vehicle behind it to fall below the minimum, the zone controller would within a few milliseconds cause that vehicle to slip back too, and so on upstream. If there would be too much slipping of upstream vehicles or if the slipping of downstream vehicles has propagated into the station area, our vehicle would wait until there is an acceptable opportunity to accelerate out of the station, thus preventing excessive congestion of vehicles in the system.

When an opening appears, our vehicle is commanded to accelerate out of the station, either from rest or from a station-advance maneuver. While our vehicle is accelerating, a vehicle ahead may be caused to slip because of a conflict at a downstream merge point. If that happens and if our vehicle would reach line speed too close behind the vehicle ahead after it is through slipping, our vehicle is commanded to slip the necessary amount while accelerating and, if necessary, the mainline vehicles behind it will be commanded to slip by the amount needed to maintain minimum headway. Next, suppose our vehicle approaches a line-to-line merge point. As it passes a command point at a predetermined location upstream of the merge junction, the cognizant wayside zone controller, having in its memory the positions, speeds and slip-manuever data for each vehicle within this merge zone, gives maneuver commands needed to resolve any conflict. If the vehicle ahead on the other branch of the merge is too close, the zone controller commands it to slip ahead if possible, or if not, it commands our vehicle to slip back. Slipping ahead is practical only if the minimum line headway is less than about one second, otherwise the maximum travel distance to slip is excessive. If our vehicle is commanded to slip back it may slip into the headway domain of the vehicle behind on the same leg of the merge, in which case that vehicle and possibly vehicles behind it are commanded simultaneously to slip necessary amounts. Since our vehicle may thus already be slipping when passing the command point, the on-board maneuver algorithm is designed so that it can cause additional slip of a slipping vehicle. Such operations have been found by simulation to be completely stable.

After passing the merge point, suppose our vehicle next approaches a diverge point. At a predetermined command point upstream of the diverge, the cognizant zone controller requests our destination, which is transmitted through a transmission medium to the zone controller. The diverge zone controller has in its memory a switch table giving the left or right switch command for each station in the network from that diverge point. By fiber optic line, the central computer can transmit revised switch tables to various diverge-point zone controllers every few seconds if necessary to avoid excessive congestion in certain downstream links. The zone controller transmits the right or left switch command to our vehicle, which then acts on the command.

Next suppose our vehicle approaches a station. As soon as it has passed a merge or diverge point, it is handed off to a new zone controller which asks for and receives its destination. If this station is not our destination, the zone controller commands our vehicle to switch in the direction opposite the station off-line guideway. If this station is our destination, the zone controller does not give a switch command immediately but waits until our vehicle reaches a switch command point at the farthest downstream point at which the switch can, with a tolerance, be safely thrown. The wait is necessary because the station may have been full when our vehicle first entered the domain of the cognizant zone controller, but the last position in the waiting queue on the station off-line guideway may have cleared a few moments later.

When our vehicle reaches its destination station's switch command point, the zone controller commands it to switch in the direction of the station if there is an available berth, and if not commands it to switch away from the station. If the zone controller commands our vehicle to switch into the station, it assigns it a berth so that the next vehicle will find that this berth is reserved. Our vehicle switches if necessary and continues forward at line speed to a deceleration command point. At this point, if one or more positions downstream of the assigned berth have cleared, a new farther-forward position is assigned, the old one is cleared, and our vehicle is commanded to decelerate along a speed profile that first reduces the speed to a predesignated station speed and then moves the vehicle forward, usually at station speed, until it must decelerate at the comfort rate to stop at the assigned position. If, at any time during the deceleration maneuver, the zone controller has advanced a vehicle out of the position or positions ahead of the assigned position, it reassigns our vehicle to the forward-most empty or to-be-empty position and revised the deceleration maneuver accordingly.

If our vehicle must stop at one of the waiting positions upstream of the station unloading and loading berths, it waits until the zone controller can command it to advance into a loading berth. If, any time during the station-advance maneuver, the berth ahead of the previously assigned berth clears, the station-advance maneuver is revised to dock our vehicle at the new forward-most free berth. When our vehicle stops, the door automatically unlocks.

The reader may note that some PRT designers have proposed that there

be separate loading and unloading platforms. This doubles the station length, reduces the throughput, and with the small passenger groups characteristic of PRT it does not significantly reduce the time required for unloading then loading.

Synchronous, Quasi-synchronous and Asynchronous Control

In the early 1970s, the discussion of PRT control virtually always started with a discussion of the relative merits of synchronous, quasi-synchronous, or asynchronous control. In a purely synchronous control system, a vehicle that is ready to leave a station waits until it has a confirmed reservation through every merge point and at the destination before being dispatched. Such a system was discarded because it is inflexible in a slow-down or stoppage on the main line; and, if the number of merges that must be negotiated exceeds three or four, the wait time becomes excessive [Anderson, 1996]. The quasi-synchronous system was therefore proposed to permit vehicles to maneuver to resolve merge conflicts.

In his book, Dr. Jack Irving, while advocating quasi-synchronous control, commented that the essential point is that a wayside computer command and monitor maneuvers, just as described above. Until reaching a merge point, there is no need to synchronize the flow, and to do so in advance results in more maneuvering than necessary. As in the scheme described in the above paragraphs, whenever a vehicle arrives at the merge command point, if there is an approaching conflict, a merge-point zone controller either commands the conflicting downstream vehicle on the other leg of the merge to slip ahead if possible, or if not to slip the vehicle that has just arrived at the command point back. There is no need at merges to synchronize with specific clock times. We have also found that the described strategy requires less software than quasi-synchronicity.

Such a scheme is asynchronous except for the technicality of having to synchronize merging of certain vehicles with respect to one vehicle, but not with respect to a clock. In the 1970s, asynchronous control usually implied car following, in which each vehicle is controlled based on the position and sometimes the speed of the next downstream vehicle. As pointed out above and by Dr. Irving, car following is not necessary. It complicates the control problem and is difficult for the necessary wayside monitor because the monitor does not know independently the profile of the maneuver. In the terminology used in the 1970s, the system we prefer could be called an "asynchronous point follower."

Movement of Empty Vehicles

During the night when there is little or no traffic on the system, most of the vehicles are stored at strategically located storage barns and the rest are stored at stations so that, as in elevator service, passengers don't need to wait anx-

iously on deserted platforms, but instead vehicles that are ready to leave immediately wait for passengers. The number of vehicles required to wait at each station must be determined by an operational study.

As passengers start arriving at stations, the waiting empty vehicles are used up and more must be ordered. Based on operational experience, a flow of empty vehicles can be started in anticipation of passengers. In any case, once the number of vehicles in a station that have not been given destinations plus the number within a specified time of arrival is less than the number of passengers waiting, the station computer signals to the central computer via fiber-optic line that it needs an empty vehicle. Other stations will have surplus empty vehicles either because they have no passengers and there are more vehicles in or approaching the station than the specified minimum, or because the flow of occupied vehicles in and approaching the station exceeds the flow of passenger groups entering the station from the street. In the later case, it will sometimes be necessary to dispatch an empty vehicle while a passenger group is approaching it in order to permit occupied vehicles to enter the station and unload. In this case, the passenger group will be informed by computer voice that another vehicle will be docking in a few seconds. As soon as a station has a surplus vehicle its computer so informs the central computer and dispatches the surplus vehicle to the next station.

When an empty vehicle reaches the switch command point of a station, if the station does not need an empty vehicle its computer waves it off to the next station. If this station could use an empty vehicle, it would like to call this one in, but there may be a greater need for it at a downstream station. So, the central computer, having a knowledge of the number of empty and occupied vehicles in each link in the network and of the number and wait time of passenger groups waiting at each station, has the basis for determining whether each station should accept or wave off needed empty vehicles. Since the situation is updated every few seconds, no passenger group need wait much more than at other stations. The average wait time can be reduced by increasing the number of empty vehicles in the network, but at the expense of increased congestion and system cost.

The major decision points for distribution of empty vehicles are the diverge points. Here, as already mentioned, the central computer, with knowledge of the whole system, can, by fiber-optic link, direct left or right switch commands for the next empty vehicle. Such frequent updating of empty-vehicle commands at the last possible moment is a far easier problem to solve than the general transport problem.

Information Transfer

With the above described control strategy, the information that must be fed to the vehicle computer is the vehicle's actual speed and position; the cruising speed, which could be a function of wind or position in the guideway; and, at command points described above, the number of a maneuver with a parameter. The information required by each wayside zone controller is all vehicle positions and speeds in its domain including hand-off of the state of each vehicle as it enters its zone,

and any information about anomalies. The information needed by the central computer is the maximum passenger wait time at each station, the stations at which there are surpluses or deficits of empty vehicles, the number of empty and occupied vehicles in each link, the destinations of and the departure times of all vehicles commanded to leave stations, the arrival times, the distance each vehicle has traveled, the distance traveled at which each vehicle is due for maintenance or cleaning, the location of and data on any faults in the system, and the weather conditions.

To perform the required data transfer there must be a continuous and noise resistant means for data transfer between vehicles and zone controllers, such as the three-wire communication line developed by Boeing [Nishinaga, 1981; Nishinaga and Colson, 1983], a series of magnet markers to signal passage of vehicles, and fiber-optic links between the central controller and all zone controllers. At predetermined intervals (Boeing used 40 msec), each vehicle must transmit to the cognizant zone controller its vehicle number, speed, position, destination on call from the zone controller, and any data about faults. The wayside zone controller must be able to transmit to all vehicles in its domain a continuous cruise-speed signal, and it must be able to transmit parameterized maneuver commands and switch commands to specific vehicles when needed.

Boeing engineers [Lang, and Warren, 1983] found that incremental wheel angle encoders with a resolution of 0.04 foot per pulse were sufficient as the basis for computing both position and speed. Position measurement consisted only of counting pulses, but the calculation of speed was "considerably more complex and, to a large extent, dictated the Programmable Digital Vehicle Control System configuration" they selected. The vehicle must also be equipped with sensors to detect the magnetic markers and to transmit to and receive data from the communications line.

Mathematics

Maneuver equations

Parameterized equations are needed for all of the maneuvers required to run a PRT system as described. This is not an easy task, but once the algebra is worked out and verified, as we have done, it is available forever. The equations can easily be programmed into the memory of the on-board and wayside computers, which then permits accurate control and monitoring of each vehicle with a minimum of data transfer.

Curved-Guideway Equations

In the above discussion, reference was made to the location of certain command points. Determination of the positions of all such points requires a complete understanding of the equations of curved guideways and their use in minimization of off-line guideway lengths and distances between branch points.

Empty-Vehicle Movement

A general scheme of the points and times in the system where empty vehicles are to be redirected has been given and the use of decision algorithms has been suggested. In relatively small systems, these are quite simple, but the challenge is to optimize such algorithms as the network grows. Some good work [Irving, Bernstein, Olson, and Buyan, 1978] has been done on this problem, but more is needed.

Conclusions

Analysis, simulation and hardware experience has shown that the problem of precise longitudinal control of vehicles to follow predetermined time-varying speeds and positions has been solved. To control vehicles to the required close headway of at least 0.5 sec, the control philosophy is different from but no less rigorous than that of railroad practice. Available results show that a PRT system can be designed with as good a safety record as any existing transit system and, because of the ease of adequate passenger protection, quite likely better.

With maneuver equations derived in easily programmable form, one has the basis for the control of a fleet of PRT vehicles of arbitrary size. The author's conclusion is then that the preferred control strategy is one that could be called an "asynchronous point follower." Such a system requires no clock synchronization, is flexible in the face of all unusual conditions, permits the maximum possible throughput, requires a minimum of maneuvering and a minimum of software. Since each vehicle is controlled independently, there is no string instability. Since the wayside zone controllers have in their memory exactly the same maneuver equations as the on-board computers, accurate safety monitoring is practical. To obtain sufficiently high reliability, careful failure modes and effects analysis must be a key part of the design process, and the control computers must be checked redundant. Work of the federal Advanced Group Rapid Transit Program showed a decade ago how that can be done in a very satisfactory manner.

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This paper was developed while the author was CEO of Taxi 2000 Corporation.