The PRT Project
Phase 1 Design & Engineering

PRT Control Strategy

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1 Executive summary

In this chapter we calculate the minimum safe headway and prove that under the current limitations on deceleration and reaction time a 2 second headway would be safe at a speed of 10 meters/sec.

Different control system strategies are introduced and the pros and cons of synchronous and asynchronous control are summarized. Our recommendation is to use point-synchronous - control, which means asynchronous with synchronism in merge points. This solution is flexible, robust against disturbances and allows system expansion.

Strategies for merging and routing are presented which take advantage of the flexibility offered by asynchronous control. This flexibility enables control to give priority to links with queues or large flows. Dynamic routing helps to avoid congested parts of the network.

The efficient redistribution of empty vehicles has proven to be crucial to achieve short waiting-times. We introduce a 3-step procedure to reduce maximum wait and total running distance.

Platooning of vehicles would be a way to increase guideway capacity. The recommendation is to apply platooning only for empty vehicles, which can run at 5 meters headway distance while the headway for loaded vehicles is 20 meters.

Finally we suggest a strategy for distribution of control to the maximum extent possible. Distributed control is less vulnerable to computer failure or loss of communication.

2 Strategy

2.1 Introduction

Controlling PRT vehicles is radically different from controlling mass transit vehicles. With small vehicles they have to run at short intervals to offer sufficient capacity. Fixed block control cannot be used. The demand situation is very dynamic and we seek to satisfy demand with virtually no waiting at stations. Empty vehicles need to be redistributed to where demand is expected. Safety must be ensured at all times.

Special control techniques have been developed to handle PRT systems operation and they will be described in this chapter.

This document discusses safe headway in section 2.2. Sections 2.3 and 2.4 discuss different control strategies. Sections 2.5 and 2.6 discuss vehicle control and merging. Sections 2.7, 2.8 and 2.9 discuss fleet management. Sections 2.10 and 2.11 present design philosophy and recommendations.

2.2 Minimum safe headway

The minimum safe headway can be determined from the brickwall safety requirement, maximum speed, maximum acceleration/retardation, reaction time and manoeuvre slack.

Brickwall safety requires that even if a vehicle suddenly would come to a standstill then the following vehicle must be able to stop before colliding with the standing vehicle.

Suppose the maximum speed v = 10 m/s, max acceleration a = 4.2 m/s^2 (has been proven to be safe) and disregard jerk limitation in emergency stopping. The stopping distance from brake application is $v^2/2a$ = 12 meters.

Our vehicle is 3 m. If we allow 0.15 seconds to detect a standing vehicle and another 0.2 seconds to apply brakes that adds 3.5 meters at 10 m/s. If we allow another 1.5 m for manoeuvring at speed changes then the minimum headway distance (nose-nose) is 20 meters and the time headway is 2.0 secs.

If the maximum speed was 12.5 m/s then by the same method the distance headway would be 18.5 + 3 + 4.5 + 1.5 = 27.5 m and the time headway 2.2 secs. We have assumed that emergency braking rate is 4.2 m/s^2 regardless of load (multiple calliper brakes) and have not included allowance for downhill since the plan is to have permanent magnets to reduce speed downhill.

Increasing top speed from 10 to 12.5 m/s would add 8 + 8 = 16 m to each station, reduce capacity by a factor of 2.0 / 2.2 = 0.91 and increase power requirements by 56 %.

The 1.5 meters manoeuvre slack can be used to reduce station length. Vehicles can start to slow down already on the main track. In our example and with a jerk limitation of 2.5 m/s^3 it takes 1.65 secs before a vehicle is 1.5 m behind.

That means it can start slowing down 16.5 meters before it is clear from the main track and the station can be made 16.5 m shorter in each end! On the exit track, the same shortening means that the vehicle comes out 1.5 m in front of its intended position and slides back while accelerating to the mainline speed. By using the extra slack of 1.5 meters between vehicles we gain 33 m on each station. The 1.5 m slack is also utilized at other speed changes such as when a vehicle has to slow down to avoid a merge conflict.

We recommend starting operation with speed 10 m/s and headway 3.5 secs. In time we can trim headways down to 2.0 secs or we can trim to 2.2 secs and allow speeds to increase up to 12.5 m/s in parts of the network.

2.3 Synchronous control

In a synchronous control system all vehicles on mainlines (not stations) follow moving "slots" at constant time headways and normally at the same speed. A vehicle is not allowed onto the mainline until a free slot has been allocated all the way from the origin to the destination. A central booking system controls allocations of time-slots in all possible conflict points, viz. network merges including station exits. Provided all vehicles are able to keep their speed then no conflicts will occur and hence no need to slow down. There will be no queues in the network but passengers will have to wait for departure until a free slot has been found. For a long trip in a heavily loaded network it may take a significant time before such a slot is found. For practical purposes the network generally cannot be loaded above 65 % of full capacity.

Synchronous control at first seems to be an attractive alternative because it is conceptually simple. Vehicles move at constant speed so the LIMs on the guideway can be dimensioned for cruising only.

Synchronous control suffers from the following weaknesses, which we will discuss one by one:

Depends on all vehicles to keep their speed
Not serious. Since vehicles are pushed there is less risk of a failure. Only risk would be a broken wheel or bearing. This can be monitored.

Does not allow change of destination
Not serious. Change of destination can be made by stopping at the nearest station and then receiving a new path.

All scheduling is centralized
We rely on the central computer as well as the communications working at all times. We can double computers and communication links to reduce the risk. If we lose control all vehicles have to stop and we need a fallback mode to move them (low speed, distance control and merge control, i.e. asynchronous!).

Cannot use full link capacity
This is not serious for Fornebu. Each trip passes only one bottleneck (out of Lysaker or into Lysaker) and we can fill those links to capacity.

Cannot be expanded into large systems
We could live with that too. We could separate a large network into smaller synchronous units with enough buffers between them. Dimensioning the buffers would be a problem – being rejected from a buffer is as bad as being rejected from a station.

If a vehicle cannot enter a station
This is serious. The vehicle has to continue and loop back without being booked through that extra loop. We can reduce the risk for a station being full by making it larger and by warning the station that a vehicle is approaching. Most often it is possible to make room by pushing out vehicles but it can happen that a slow passenger does not get ready in time.

We can keep station exits free but generally not the other merges. We can sometimes create a free slot by allowing a vehicle to slip back to an empty slot behind (quasi-synchronous control) if there is one.

Another possibility would be to have double headways normally so that one vehicle can go in between if necessary. That would reduce capacity to half.

Another possibility would be to run at unsafe headway until the next station.

Another possibility would be to go down to a low speed that would allow half the time headway. With 2 seconds headway and with our assumptions on reaction time and vehicle length there is <u>no speed</u> at which a 1 second headway is safe or even physically possible!!

The final possibility which remains is to slow down all vehicles in the network to allow shorter headways and then create a free slot by pulling together enough vehicles on a link. This would be a very asynchronous manoeuvre. A synchronous control system would therefore need an asynchronous fallback routine!

Our conclusion is not to recommend synchronous control even though it would have saved half of the LIM controllers on the mainline and about 5 % of the total system cost for Fornebu.

2.4 Asynchronous control

With asynchronous control vehicles are allowed to start as soon as the mainline is free. Local merge controllers resolve possible conflicts and some vehicles may have to slow down or even queue before they can pass through a merge. The system works much like cars on roads and streets. Congestion may occur and traffic control tries to avoid queues from building up. Control is local between vehicles and the next downstream node. A disturbance will only affect one link except that queues may spill back into other links. Link capacity can be utilized up to 100 % and route changes are possible during a trip.

Point-synchronous control is one way to resolve merge conflicts in an otherwise asynchronous system. As a vehicle enters a link leading to a merge (including station exits) it is allocated a passage time through that merge. The vehicle speed is adjusted to meet that passage time. Vehicles are made to pass through merges in synchronism. There is no need for a global clock and each merge controller clock can be reset whenever headway is longer than the minimum. The merge controller ensures that safe headways are maintained through the merge.

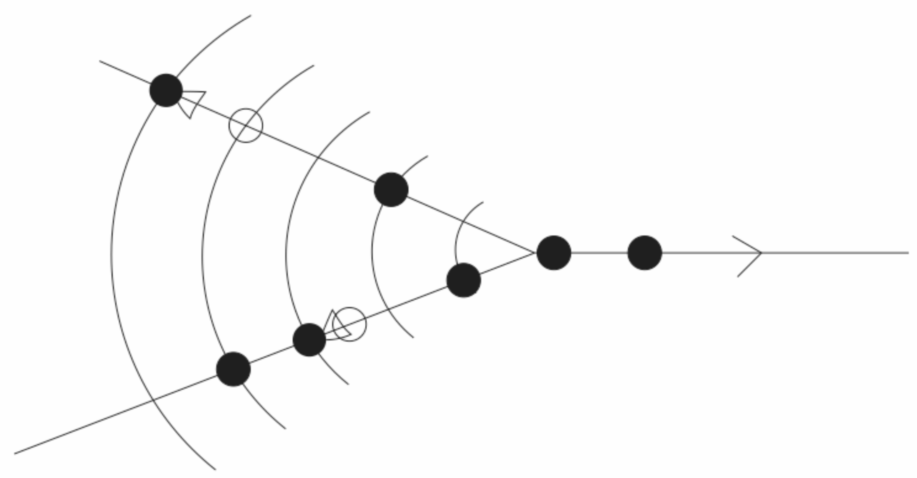

Figure. With point-synchronous control the merge controller will allocate passage times to approaching vehicles so that they pass the merge at safe headways and at nominal speed.

We recommend the use of point-synchronous control. Control is decentralized to each conflict point (merge) and there is flexibility to change routes along the way. That flexibility is used to avoid queues building up and to move empty vehicles in the most efficient way. There is no limit as to how large a fully decentralized system can grow.

When an asynchronous system gets overloaded some queues get longer but that is a graceful decline and it can be resolved without special fallback procedures. Before reaching that level of congestion we would encourage or enforce more ridesharing. With ridesharing the expected demand at Fornebu for year 2015 can be handled at 3-second headways and we can handle 2-second headways safely.

2.5 Positioning

For the control of guideway-mounted LIMs it is necessary to know in every moment the position and speed of each vehicle. That same information is also used by the downstream node controller in charge of normal control. The information is also passed on to central supervision and control. Central control may decide to change the destination of an empty vehicle or other vehicles in irregular situations.

In order to minimize dependence on communication it is preferred to determine positions and speeds from the guideway. From the guideway the information is sent via cable to the next downstream node.

A guideway-mounted detector is to identify the presence of a vehicle, how far it has passed and at what speed it is going. The distance between detectors is one vehicle length or less. Notches along the vehicle side can be used to count how far it has passed and the frequency of notches indicates vehicle speed. Certain information such as identity, destination and load is transmitted from the vehicle to a guideway-mounted detector.

2.6 Merging rules

Merge nodes are the only points of possible conflicts in a PRT system. The role of a merge controller is to resolve these conflicts by controlling approaching vehicles on the input links. By giving priority to one or the other oncoming vehicle additional beneficial effects can be achieved.

In a point-synchronous control system, vehicles report to the downstream node as soon as they enter a link. The merge controller will allocate a time for each vehicle to pass the merge so that safe distances are maintained. If the vehicle does not receive a passage time message it must stop.

By choosing which vehicle to let through several objectives can be met:

- Priority to the link where the queue is closest to the next upstream node will minimize the risk for a queue to spillback beyond one link

- Weaving empty vehicles together whenever possible helps to build platoons of empty vehicles which can run without safe distance between them

- If the network tends to be congested the merge controller at a station exit can stop new vehicles from entering the main track.

2.7 Dynamic routing

Changing the route of vehicles as they run is possible with asynchronous control and adds important flexibility to a PRT system in the following ways:

1. If a passenger in a vehicle has made an emergency call then that vehicle can be redirected to the nearest station or to a station with staff or police

2. In cases of disturbances or a vehicle queue on a link it is sometimes possible to redirect vehicles to avoid that link

3. Empty vehicles can be redirected to give priority to passengers who have been waiting the longest

Quickest routes from each diverge to each destination are recalculated at regular intervals taking into account experienced delays in the network. Delays can be exaggerated so that early tendencies to congestion on a link cause routes to avoid that link whenever possible.

When a vehicle enters a link leading to a diverge, it calls the diverge controller, reports it destination and whether it has an emergency. The diverge controller will report back to that vehicle with instructions to turn left or right in that diverge. If the vehicle does not receive any instruction it must stop.

For vehicles to be able to react immediately to an incident or a sudden congestion the decision by the diverge controller can be based on current travel times on the outgoing two links (reported by the downstream node) and expected travel times from there on to the destination, based on tables. This method can be extended to use current link times for two or more links ahead.

2.8 Empty vehicle management

Empty vehicles become available at trip destinations and they are needed at trip origins. Travel demand is generally not balanced so it is necessary to redistribute empty vehicles. Redistribution is based on waiting passengers and expected new passengers at each station and vehicles already on their way to the respective stations. The objectives of empty vehicle management are threefold:

1. Minimize average passenger waiting-times
2. Minimize maximum passenger waiting-time
3. Minimize total empty running distance

The problem is complicated by the fact that there is no dedicated storage space for empty vehicles at stations. Empty vehicles frequently have to be pushed out to make room for arriving loaded vehicles into the station track and on to the platform.

Efficient redistribution becomes more critical the larger the network is. As distances grow the time to call an empty vehicle gets longer but passengers do not accept longer waiting. Also the problem is most critical when the system runs near capacity when most of the vehicles are occupied.

Decisions on sending empty vehicles have to be made instantaneously for one vehicle at a time. On the other hand we need to overview all supplies and demands in order to optimise redistribution.

The following procedure has been developed by us and has proven efficient in simulations. Decisions on destinations for empties are made by three different procedures.

1. Supply and demand is estimated for each station.

Supply is taken as

- vehicles in the station
- minus vehicles scheduled to depart
- plus vehicles on their way towards this station

Demand is estimated as

- passenger parties queuing to depart from the station
- expected new passenger parties during the expected time to call an empty vehicle

The call time is continuously updated for each station (smoothed average).

A call for an empty vehicle is considered each time a passenger arrives if a deficit is predicted.

Sending an empty vehicle is considered each time a vehicle arrives to a station if
- enough vehicles are present to serve waiting passengers
- and a surplus is expected at the station
- or if the entry track gets full
- or a loaded vehicle needs access to the platform.

A called vehicle is taken from the largest surplus (irrespective of distance) or from the depot if no station has a surplus.

The destination of a vehicle to be sent is the largest deficit or the depot if no station has a deficit.

The innovation in the procedures 2 and 3 below is to allow change of destination as an empty vehicle runs. This is important because new passengers show up and empty vehicles become available unexpectedly.

2. In the second procedure waiting passengers are given priority in order to minimize the longest wait. The "oldest" waiting passenger gets his nearest upstream empty vehicle regardless of the previous destination of that vehicle. Then the next oldest waiting passenger gets a vehicle until all waiting passengers have been served.

3. As a final step the remaining empty vehicles are allocated to remaining destinations so as to minimize total running distance. This is a classic optimisation problem called "transportation problem" originally conceived for the distribution of goods from several factories to several customers.

2.9 Platooning

The minimum safe headway between vehicles was introduced in order to ensure passenger safety. Empty vehicles can run at shorter distances if the control system can handle that. Platooning empty vehicles increases capacity on the mainlines. At 10 m/s and 2 secs headway the normal distance headway is 20 meters. Shorter distance can be used in queues and for empty vehicles.

Loaded and empty vehicles normally come intermixed so we cannot always take advantage of platooning. Adjusting the rules for merging helps to form platoons of empty vehicles.

2.10 Levels of control

As a design philosophy we wish to keep central control to a minimum so that critical control functions are distributed. This is possible with asynchronous control and it makes for a less vulnerable control system.

The following control functions need to be handled centrally.
• Demand forecasting
• Empty vehicle management
• Calculation of quickest paths
• Emergency calls
• Maintenance planning
• Collection of statistics (system performance, weather, events…)

The following control functions should be performed at each station:
• Demand statistics on 5-minute levels over a week
• Ticketing (information, issuing, payments)
• Coordination/information for ridesharing
• Pushing out empties blocking other vehicles
• Open/close platform doors

The following control functions can be performed by a diverge (switch) controller:
• Communication with oncoming vehicles
• Direct an oncoming vehicle depending on its destination and network conditions
• Controlling vehicle movements on the upstream link

A merge controller can handle the following functions:
• Communication with oncoming vehicles
• Allocate passage times for each vehicle based on merging rules
• Control vehicle movements on the two upstream links

The following control functions can be handled from the guideway:
• Reading the position and speed of each vehicle
• Receive information from vehicle (id, destination, load, emergency…)
• Communicate with the downstream controller
• Control LIMs based on commands from downstream controller

The vehicle needs the following control functions:
• Receive destination from ticket reader (inside or outside vehicle)
• Receive ready signals and emergency signals from passengers
• Engage the vehicle switch based on instructions from switch controller via guideway
• Activate emergency and parking brakes
• Open left or right door upon command from station

2.11 Conclusions and recommendations

- Minimum safe headway at 10 m/s is 2 secs and 20 meters nose-nose
- Asynchronous control is best suited to handle disturbances, allowing dynamic routing and expansion into large networks
- Asynchronous control is not critically depending on communication with a central computer.

We recommend to start with a longer headway, say 3.5 secs and trim as we learn more about delays and precision (to 2 secs at 10 m/s or 2.2 secs at 12.5 m/s).
A manoeuvre slack of 1.5 meters, which is allowed within the 2 secs headway, saves 33 m on each station.