

January 17, 2019

IS THERE A CASE FOR HIGH SPEED, HIGH CAPACITY ATN/PRT SYSTEMS?

OVERVIEW

Since its initial introduction in the U.S. in Morgantown West Virginia in 1975, the concept of Automated Transit Networks (ATN; also called Personal Rapid Transit, PRT, or Group Rapid Transit, GRT) has struggled to achieve widespread acceptance as an approach for public transit. Despite the initial enthusiasm for the Morgantown project, other cities have not embraced the ATN concept as an attractive mode of public transit, while cities around the world continue to spend large sums of money to deploy conventional metro rail systems.

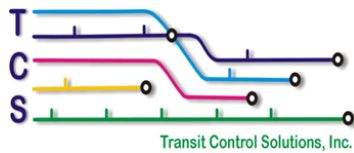
In the analysis presented here, ample and fundamentally-sound reasons have been identified for the ATN/PRT concept to be promoted as more than a first/last mile mode of transport. Adoption and deployment of this concept would require the industry to embrace the automated, driverless vehicle control concepts that have now been pioneered by Transit Control Solutions, Inc.

BACKGROUND

In 2006, the R&D division of the San Francisco Bay Area Rapid Transit District (BART) investigated the ATN concept and its potential value as an approach for expanding the service territory of BART. With knowledge of the experience at Morgantown, the investigation sought to understand why the Morgantown experience was never replicated in the United States or elsewhere and whether it was time to revisit the lessons learned from that experience. A key conclusion of this effort was that limitations associated with the control technology for driverless vehicles made the concept inadequate for cost-effectively addressing the needs of transit. However, the investigators reported on several virtues associated with use of off line stations, which, if the control issue could be addressed, would make PRT an attractive option for transit.

The control technology limitation mentioned above derives from a current design practice that assumes leading vehicles can stop instantaneously – a practice that prevents systems with off line stations from achieving traffic densities at speeds practical for regional transit applications. In fact, the prevailing design standards, like the ASCE-authored Automated People Mover Standard and the IEEE Standard 1474 for Communication Based Train Control, have mandated the current practice. However, in 2018, the case has been made to the ASCE that systems that have placed all stopping berths off line are unnecessarily burdened by this practice and the ASCE has recently decided to amend the standard as it applies to systems with off line stations. Could this change the consensus view of PRT? Should it now be considered for higher speed/higher capacity applications? This is what will be discussed in this article.

Since the time of the BART study, Transit Control Solutions, Inc. (TCS), with a group of transportation technology experts including a former member of the investigative team at BART that performed the aforementioned study, has been developing a design that enables High Speed/High Capacity PRT systems to be viable. While the focus of this article is not that new design, a brief description follows.



At the writing of this article, the current state of the art is what is referred to as Moving Block (MB) Control. In MB control systems, the positions of all controlled cars are tracked with a relatively high degree of accuracy, and the actual detected locations of the cars are used as inputs to the control logic which continuously calculates the Worst Case Stopping Distance (WCSD) of each car and fail-safely commands cars to brake if the distance to other cars becomes less than the WCSD. Given that there are delays to command and respond, and various other characteristics of the vehicle specific to every system that need to be considered, the calculation of this stopping distance requires the assumption of a braking trajectory that looks something like that shown here (Figure 1).

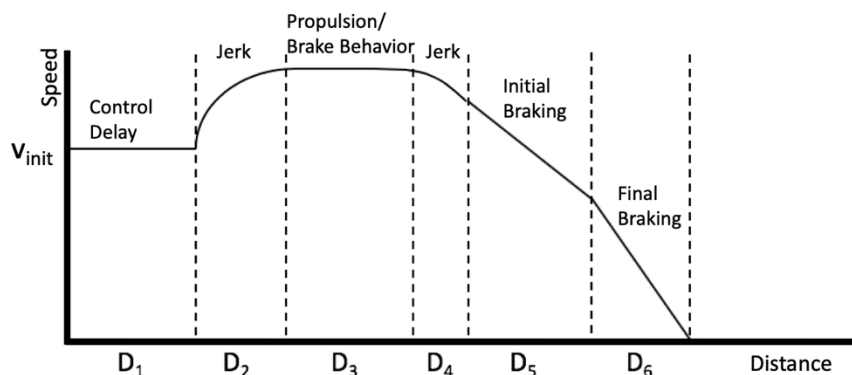


Figure 1: Example Worst Case Braking Trajectory

Since the time between vehicles is primarily driven by the stopping distance that derives from this braking trajectory, and because this distance increases roughly with the square of the vehicle speed, it is not possible to control cars to operate very close to the car in front, especially as the speed increases. The innovation introduced by the new design overcomes this problem using implementation methodologies that are consistent with current practices for the implementation of control systems and should be acceptable to existing transit agencies and the authorities that govern such agencies. The performance achieved by this new design is one-second headway between cars operating at about 60 mph (approximately 100 kph). This is illustrated by the comparative plot shown in Figure 2.

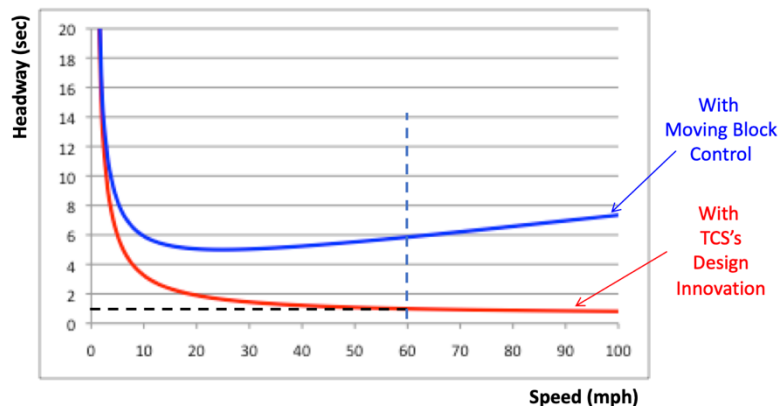


Figure 2: Comparative Plot of Headway Performance



COMPARING THE ECONOMICS OF THE ATN CONCEPT AND CONVENTIONAL RAIL

The principal distinguishing feature of the ATN concept is the use of off line stations. Conventional rail systems, in contrast, stop trains on the main line where the stopped train blocks the movement of other trains. And since trains must stop long enough for large numbers of people to embark and disembark at the station, the frequency of trains that can be operated can never be very high. This is illustrated in Figure 3 below which shows that the length of the horizontal plot for the leading train affects the time separation between the leading and following trains. In this sample illustration, the leading train has stopped for 30 seconds to let passengers offboard and onboard. If we assume worst case stopping distances must always be maintained between the leading and following trains, the time separation or headway can never be less than about 95 seconds. If the stop in the station were longer, time separation between trains would be even longer. This is true with even the most advanced Moving Block implementation. In addition, transit operators typically schedule trains to run about 1.5 times the separation required for safety in order to enable schedule recovery. Thus, a system capable of operating trains 95 seconds apart might typically schedule trains to run about 140 seconds apart.

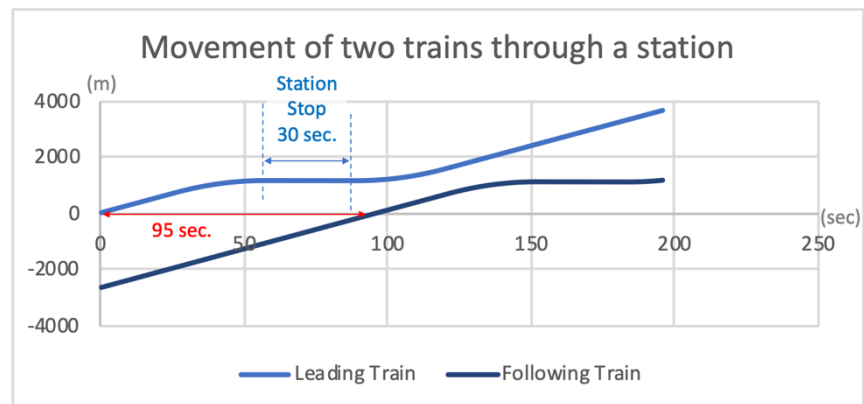


Figure 3: The Effect of Stations on Throughput

ATN vehicles, in contrast, stop to let passengers get on and off the transit system at locations where the vehicle is not an obstruction to through traffic. What results is a system whereby: 1) vehicles can travel faster to a destination by bypassing stations along the way, and 2) higher vehicle traffic densities can be achieved on the through tracks, which in turn means many smaller and thus lighter cars can be used instead of long heavy trains.

Clearly, the ability to shorten travel times is a virtue and represents more value. However, is it more cost effective from both a capital and operating cost perspective to use many small cars rather than to use a relatively small number of large trains?

The answer to this question is a matter of benefit/cost. In other words, for some measure of performance, how does the cost of an ATN system that serves the public with smaller and lighter cars compare with that to construct and operate a traditional metro rail transit system?



Capital Benefit/Cost

The potential virtue of the ATN concept is its ability to use small cars that can run on much lower cost infrastructure than what is required for supporting large heavy trains typically used for conventional transit. Today, conventional above-ground metro rail systems cost in the range of approximately \$100 million per mile to construct. Even at such a price, the service they provide is invaluable to the community and the benefit/cost is considered to be good. The question of importance is whether the ATN concept represents a more cost-effective approach. In other words, is the benefit/cost better? To answer this question, one needs to determine whether the drop in passenger carrying capacity is more than or less than the drop in the capital cost of construction as cars are made smaller. If, as the car is made smaller, the drop in capacity is greater than the drop in cost, then conventional rail has a better benefit/cost, and vice versa.

Since the use of lighter cars that can run on lower cost structures is a major driver of cost, the effect of lowering the infrastructure construction cost on the total project cost as smaller cars are used needs to be understood when considering what to build. To this end, an observation of the BART effort was that the actual labor and materials cost of constructing the infrastructure comprised about 35% to 50% of the total project cost when constructing new service lines. Examples of what constitute the balance include the cost for the right of way, engineering, project management, field oversight, various systems, environmental mitigation, and the cars. Thus, as cars become smaller, the portion of the project cost that scales well with the car size is only a portion of the total.

That being said, as cars are made smaller, there will be some reduction in non-construction costs, although not nearly as dramatic. Non-construction costs that might be affected as cars are made smaller include, for example, costs for environmental mitigation, field oversight, supporting systems (traction power for example would be less costly), and perhaps even the rolling stock. Other non-construction costs, such as the cost of engineering and the cost of project management, both a sizeable contributor to the cost, may not be affected all.

So, when examining the effect of vehicle size on project cost, the above realities need to be taken into account. This is what is attempted in Figure 4 which illustrates what would happen if we assume the infrastructure construction cost scaled directly with vehicle size but other costs not to the same degree. (Note: Except for a few points on the graph, this plot is not a plot of calculated or compiled data, but is intended to illustrate the general effect of car size on system cost.) As illustrated, the total project cost does not drop as much as might be expected, because the “other costs” dominate the cost as the cars are made very small.

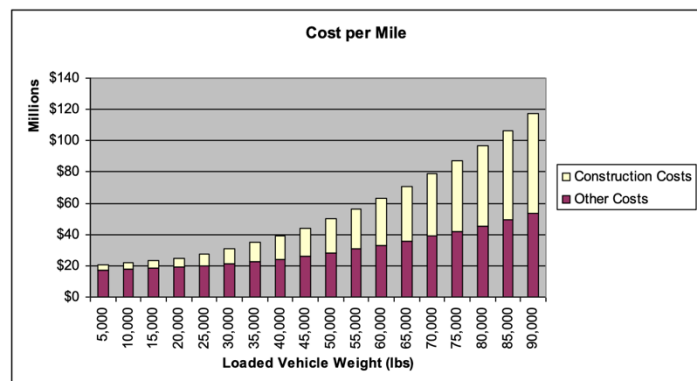


Figure 4: Effect of Vehicle Size on System Cost



The passenger-carrying capacity of a transit system, however, does scale almost directly with vehicle size. All things being equal, roughly speaking, if the number of seats in a car is halved, the number of passengers the system can carry would be halved. For this reason, as smaller and smaller cars are used, the benefit/cost becomes worse. This perhaps was a major contributor to the relative lack of success of the ATN concept until now. Of course, “all things are not equal” so the analysis is not quite so simple, but one can see the general problem – the total project cost does not scale directly with vehicle size, whereas line capacity, more or less, does.

Given what is described above, the capability of the control technology becomes key to understanding the economic case for ATNs. The closer together that cars can be safely operated, the more passengers can be served for a given car size, which in turn, improves the benefit/cost ratio. To understand the importance of the control technology with regard to the case for the ATN concept, the following plot (Figure 5) is provided. This plot compares the benefit/cost of a conventional rail system that carries 16,000 passengers per hour (approximate capacity of BART assuming no standing passengers) with the

benefit/cost of an ATN system that operates four-seat cars as a function of a range of varying safe operating headways. The red line is a plot of the ratio of the benefit/cost for the ATN system and the benefit/cost for the conventional rail system. Where the value plotted is unity (the dark dashed line), the benefit/cost of the two are the same. Where it is greater than unity, the ATN is better. Below the dashed line, the benefit/cost is worse.

Comparing a Metro Rail system with a capacity of 16,000 PPH and costing \$100 million/mile to an ATN system costing \$20 million/mile and operating 4-seat cars.

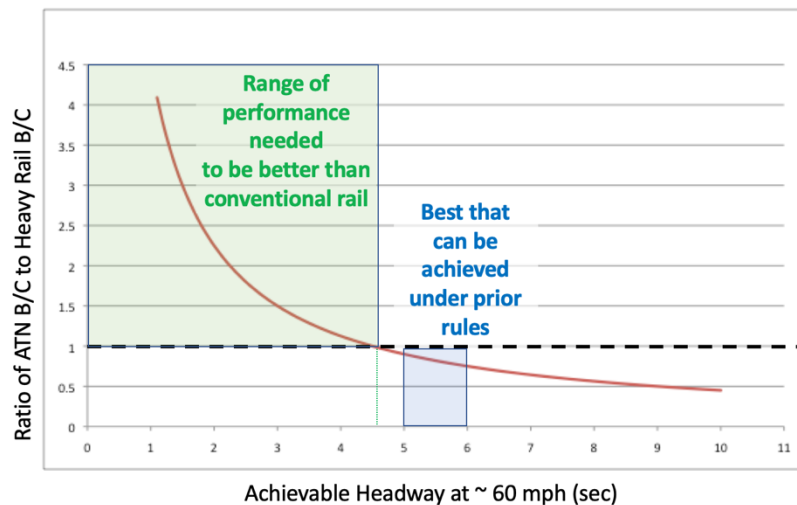


Figure 5: Comparing the Benefit/Cost of Conventional Rail to ATN

As shown, for a headway of about 4.5 seconds, the benefit/cost for the two technologies is the same. For headway times less than this, the ATN approach is better. The problem for ATNs until now is that the requirement to assume that leading cars can come to an instantaneous stop has defined the achievable headway at 60 mph to be in the range of five to six seconds. Thus, for ATNs to be superior, the instantaneous stop criteria must be changed. This is in the process of happening now, and when it does, may open the door to the lower headways required to make the case for ATNs superior to that for conventional rail.



BART-Equivalent Service

Another subject of interest for the BART researchers was to gain an understanding of whether the ATN concept is suitable for service like that which BART provides using conventional approaches. For this, an attempt was made to understand what would be required to achieve an equivalent service with the ATN approach, with “equivalence” being defined as serving the same geographic station locations, carrying the same number of riders, and achieving travel and wait times that are always less than or equal to that achieved by the conventional approach. This is now discussed in what follows.

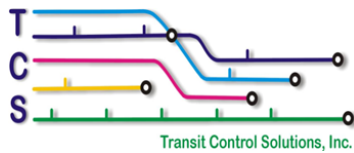
Figure 6 shows a map of the BART system as it was in 2006 when the aforementioned study was conducted. The system provides service between the communities in the East Bay (east of SF Bay, such as Oakland, Berkeley, Walnut Creek), with the city of San Francisco in the West Bay. As shown, a distinguishing feature of the BART system is that the traffic to San Francisco is comprised of traffic from four East Bay lines (A, C, L, and R) that merge together before crossing the Bay in an underwater tube (Transbay Tube) between the two sides of the Bay (San Francisco and Oakland). Since construction of the Transbay Tube was a very expensive project, the track through the tube as well as the track through the city of San Francisco, which is for the most part underground, is single track in each direction with periodic crossovers where trains can cross from one track to the other.

BART System System Map (2006)



- Mileage = distance to Wye
- Station Count = number of stations through West Oakland
- A, L, and R Lines carry a 10 car train to SF every 15 minutes; C Line every 7.5 minutes
- Average distance of East Bay lines to West Oakland is 22.5 miles
- Average number of stations of each line through West Oakland is 10
- 70% of the riders offboard in downtown SF

Figure 6: BART-Equivalent Service



The first step taken by the BART researchers was to characterize the BART service in a way that facilitated easy analysis. This resulted in the representation of the service lines illustrated in Figure 7.

In this representation of the BART system, the Major Station represents all of the stations on the line running through the city. Minor Stations are the stations at the various communities in the East Bay where the majority of the riders board to travel to the city in the morning and return in the evening.

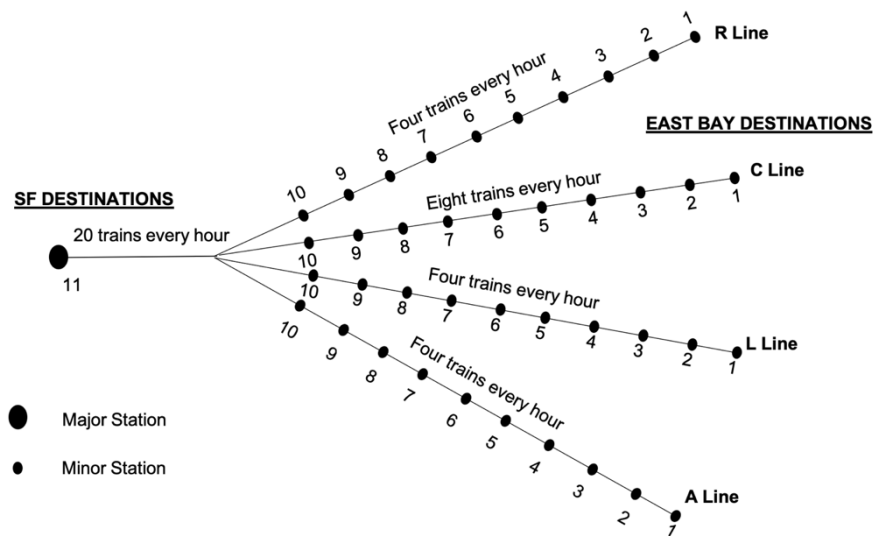


Figure 7: BART System Configuration

Examining each line individually, a typical line is represented in Figure 8 with a brief summary of the characteristics of the service provided by each.

BART Service Lines

- A, L, and R Lines carry a 10-car train to SF every 15 minutes, C Line every 7.5 minutes
- Average distance of East Bay lines to West Oakland is 22.5 miles
- Average number of stations of each line through West Oakland is 10
- 70% of the riders offboard in downtown SF
- Trip speed < 40 mph, maximum wait time < 15 minutes

Equivalent Hypothetical Service Line

- Long linear line with 11 stations with a spacing of 2 miles between stations
- 11th station is Major Station where 70% of the people offboard
- 30% offboard evenly distributed among the 10 Minor Stations
- Each single density line (A, L and R) delivers the equivalent of one 10-car train (800 seats) to Major Station every 15 minutes, the double density line (C) delivers two trains every 15 minutes
- Cruising speed = 60 mph
- Maximum acceleration rate = 2 mphps
- Minimum assured brake rate = 1.5 mphps
- Maximum grade = 4%

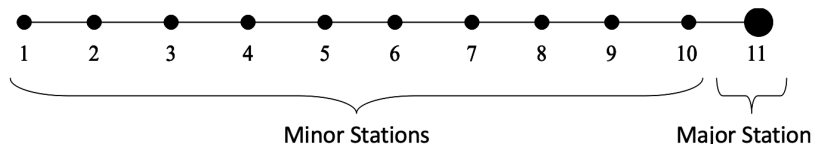


Figure 8: Hypothetical Typical Service



So, given this characterization of the BART service, how might an “equivalent or better” service be provided using the ATN approach?

Although there are likely a variety of ways to achieve equivalent service, one relatively simple approach is illustrated in Figure 9. Here what is seen are two different service patterns that can be operated. One, which we would describe as Direct Service, provides direct service to the Major Station from each of the Minor Stations and the other which we call Local Service, runs cars that stop at every Minor Station on the line but does not travel to the Major Station. Since the stations are on sidings and do not interfere with traffic on the passing tracks, the station dispatch times can be timed so that the two service patterns operate concurrently. This is effectively a service that is a hybrid of ATN and conventional rail service patterns. The Direct Service takes advantage of the ability to bypass stations whereas the Local Service operates more like a conventional system that stops the vehicle or train at every station.

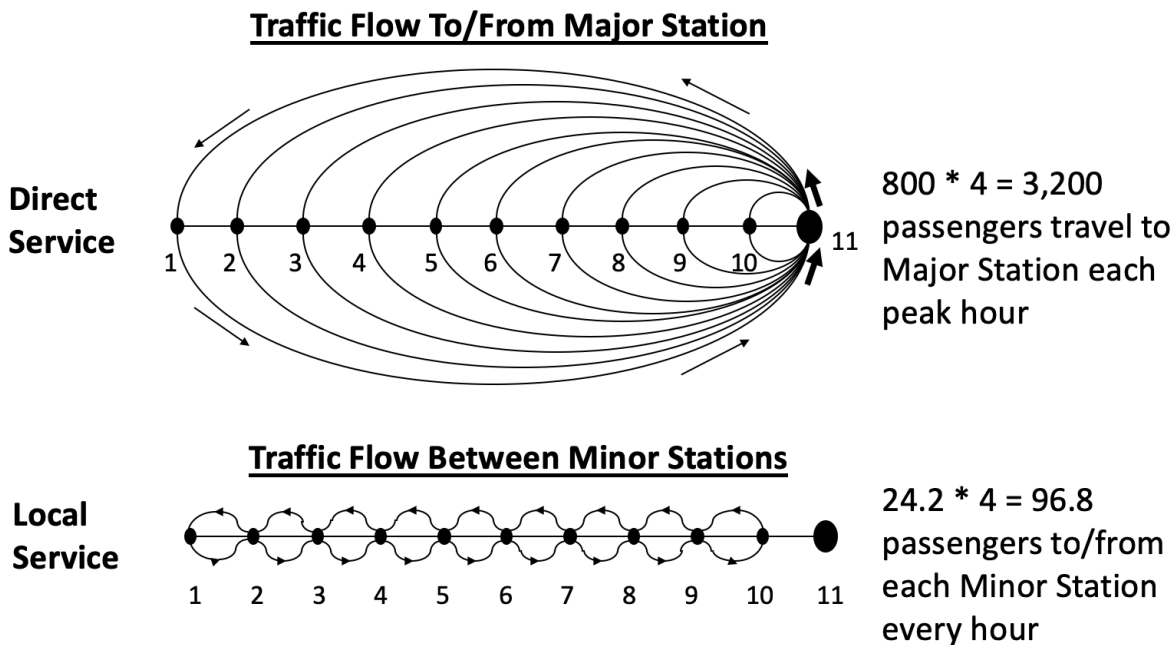


Figure 9: ATN Service Patterns That Replicate BART Service

Assuming the seats in the trains to the Major Station are filled to capacity and 800 passengers are carried per train, to provide a service equivalent to the highest capacity line (the C line) with PRT during the peak service hour(s), the number of passengers that board at each Minor Station to travel to the Major Station would be $(800 * 8) \div 10 = 640$ passengers. Assuming six-seat cars, this would require $640 \div 6 = 106.7$ cars to dispatch from each station to travel directly to the Major Station. With four-seat cars, 160 cars per hour would be required for service to the Major Station.



Since 30% of the passengers that board at a station travel to one of the Minor Stations and 640 passengers depart for the Major Station, the number of passengers that board at a Minor Station to travel to another Minor Station is calculated by letting n = passengers that depart from a station every hour and using the expression:

$$640 + 0.3n = n$$

From this we get $n = 640 \div 0.7 = 914.3$ passengers every hour. Since 640 of these passengers travel to the Major Station only 274.3 passengers travel to one of the other Minor Stations. Thus, with six-passenger cars this would require $274.3 \div 6 = 45.7$ cars for any given Minor Station. Since these cars stop at every station other than station number 11, if 45.7 cars leave one of the Minor Stations, 45.7 cars will dispatch from every Minor Station every hour and this determines how frequently the Local Service must run.

Thus, assuming six-passenger cars, the total that would dispatch from each of the Minor Stations would be the sum of the 106.7 cars to the Major Station, and 45.7 cars for the Local Service, for a total of 152.4 car dispatches per hour out of each Minor Station.

For the above frequency of service, the highest density traffic occurs on the track between stations 9 and 10. Here the cars serving the Major Station from Minor Stations 1 through 9 all operate plus the cars providing the Local Service. This sums to $(9 * 106.7) + (1 * 45.7) = 1,006$ cars per hour. For this to be possible the headway between cars would have to be $3,600 \div 1,006 = 3.57$ seconds.

For the total system, the highest density traffic occurs between stations 10 and 11 after all of the East Bay lines have merged. Here the 106.7 cars per hour from each of the stations on the C line combine and merge with the traffic from each of the other three lines, which send half as many cars per line. The total is calculated as:

$$(10 * 106.7) + 3 * \left(\frac{10 * 106.7}{2} \right) = 2,667.5 \text{ cars per hour}$$

For this, a headway of 1.35 seconds would need to be achieved which is less than what is currently possible with existing control systems. However, if this headway were possible, three corollary advantages of the ATN service that was hypothesized above were observed. They were:

Shorter travel experience – The average actual travel time was reduced by approximately 30% and the worst case wait time for any trip was reduced from 15 minutes to under three minutes. Note that passengers typically perceive waiting times to be twice as long as riding times.



Significant savings in the cost of the rolling stock – The result from calculating the number of vehicles required to provide the service with smaller cars rather than larger cars showed that every 80-seat car required for operating in a conventional manner could be replaced by two 20-seat cars operating in an ATN system. If one assumes the cost per seat to be constant, this operating efficiency results in a 50% reduction in the cost of the rolling stock.

Improved operating efficiency - To provide 45,000 passenger miles of service, the conventional approach needed to operate 85,000 unoccupied seat miles. For the ATN approach this reduced to 35,000, a significant reduction in wasted vehicle operation. An important result of this improved efficiency is the likelihood that public transit might one day be able to operate free of public operating subsidies, something that is not possible today.

Figure 10 illustrates these findings.

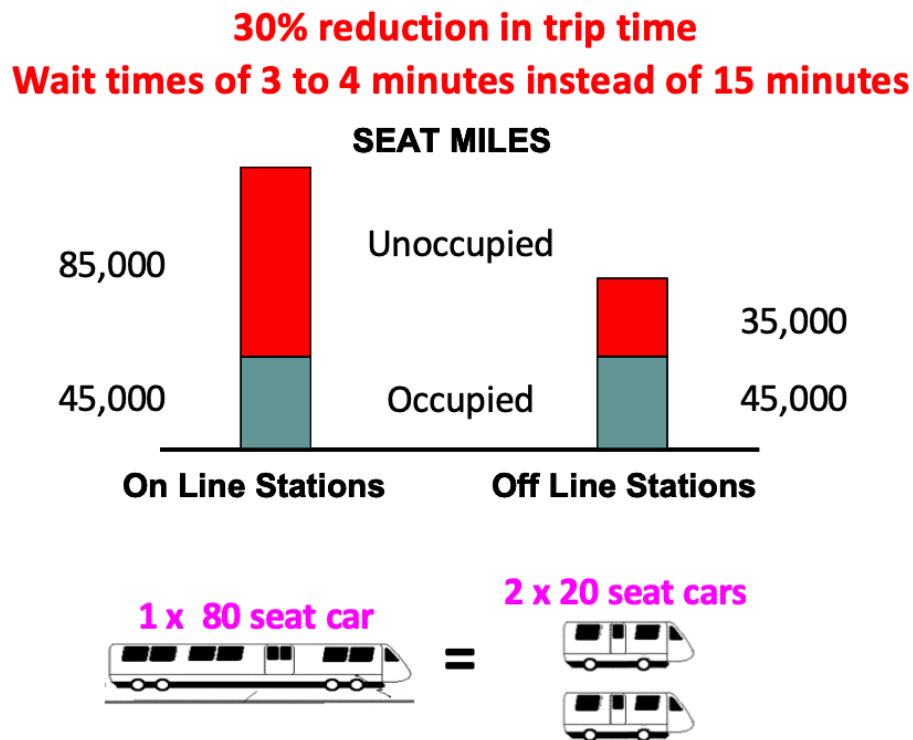
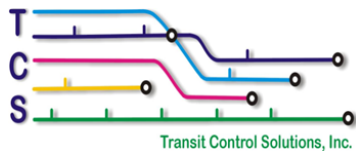


Figure 10: Improved Operating Efficiencies



NETWORKABILITY/SCALABILITY

High Speed/High Capacity PRT technology is an enabling technology that enables networkability. To explain, an illustration of our current network of paved roads is used. (Figure 11).

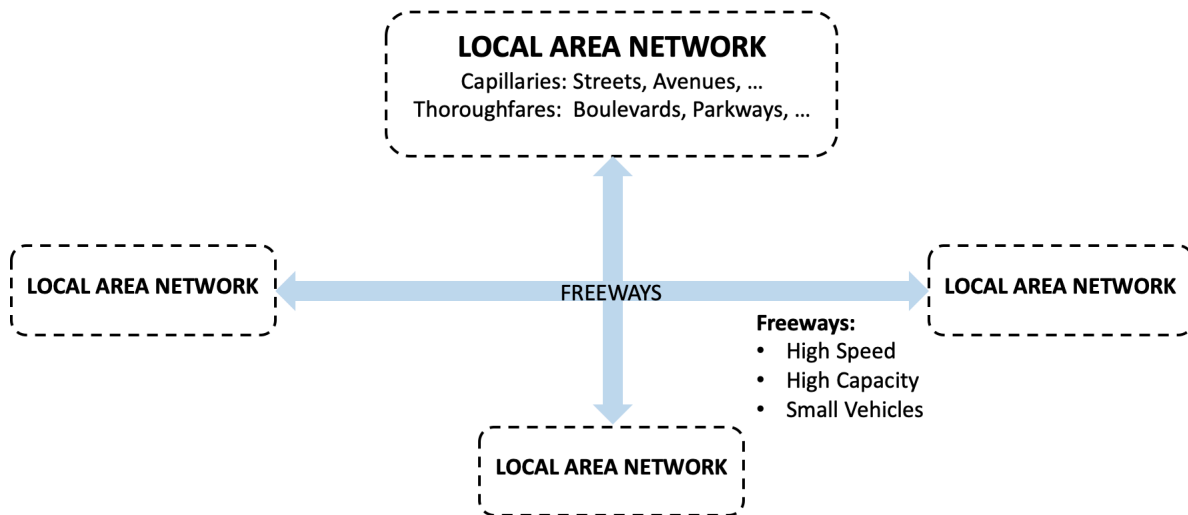


Figure 11: Freeways Enable Our Current Network of Pavement

The pavement that we use today to operate automobiles is networkable primarily because of what we refer to as “freeways.” Freeways, also referred to as “expressways” or “controlled-access highways,” are paved surfaces on which very high volumes of vehicles can operate at high speeds. Furthermore, the vehicles that travel on these roads are the same vehicles that can travel on the local networks of roads that provide access to local origins and destinations. Without freeways, roads and the cars that run on them would only be practical for local applications. Travel from a location in one local network to a destination in a far-removed community would take a long time and seriously impact the practicality of automobiles.

Fixed-route transit has never had a freeway-equivalent technology. Rail structures that are capable of handling large traffic volumes are large, expensive, and are only practical if they are used to operate long, heavy trains. This makes service deep into local communities difficult and, in most instances, impractical. As illustrated in Figure 12, if High Speed/High Capacity PRT becomes possible, then this need no longer be the case.

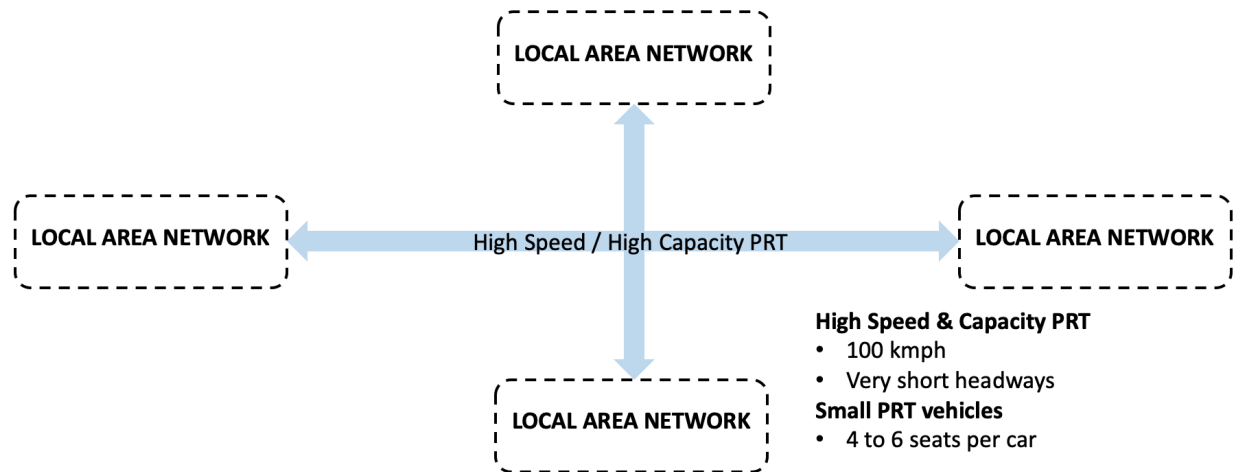
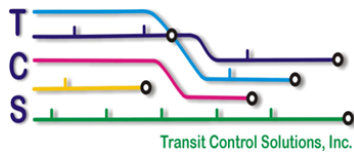


Figure 12: Networkability is Enabled by High Speed/High Capacity PRT

PRT guideways can be used to handle passenger volumes that are easily equivalent to the traffic on a four-lane freeway. And as with freeways, the vehicles that run on the High Speed/High Capacity lines can be small, light, and practical for use on guideways that connect to local origins and destinations. Furthermore, every new Local Area Network constructed could connect to the existing network, thereby having much more value than infrastructure built only for local service. In short, what is enabled by High Speed/High Capacity PRT is scalability in a major way in much the same manner as freeways have made pavement and automobiles a scalable mode of travel. Whether it will eventually become practical as a country-wide network as are roads today may be debatable but certainly regional networks in the range of 80 km (i.e. 50 mile) radius would not be out of the question and can easily be imagined.

In the U.S., there is currently a movement to build High Speed Rail (HSR). However, critics argue its practicality because HSR, to be practical, needs to space stations far apart. In the U.S., without the local transit networks to distribute riders throughout the regions served by HSR, roads and the vehicles that run on them continue to be necessary. Large regional networks of High Speed/High Capacity PRT can be the complementary transit technology to make HSR practical.



SUSTAINABILITY

Other than for fixed route forms of transportation, human mobility requires an energy source that can be carried on the motion platform. With the combustion of fossil fuels being, to date, the most convenient source of such energy, fossil fuels continue to be the predominant energy source of choice. Thus, today, more than 50% of our country's use of fossil fuels is dedicated to the movement of people and goods. Since the combustion of fossil fuels generates CO₂ one can see that transportation is a major contributor to the phenomenon of climate change.

Fixed route transit has the potential to address this problem since, when operating on fixed routes, the energy for propulsion can be delivered to the motion platform instead of carried on board. Unfortunately, fixed route transit of the past has needed to operate vehicles/trains that can carry large numbers of people since the vehicles could only travel relatively infrequently, and this has required very high levels of power to accelerate out of platforms to reach operating speeds. The BART system operates trains that when fully loaded, weigh approximately one million pounds and requires 10 MW of power to accelerate out of a station. For power at such levels, large power generators are needed, which often require the combustion of fossil fuels.

In contrast, if PRT vehicles can be used to provide a similar service, the power needed would be dramatically less. In fact, so much less that non-petroleum-based energy sources become useable and practical. One calculation concluded that solar panels on or over the trackways would generate more than enough power to propel PRT cars, and coupled with a technology for infrastructure-based electric energy storage for night-time operations, could operate as a mode that is completely independent of petroleum-based energy sources and is therefore potentially fully sustainable.

SUMMARY

The following summarizes the key points made in this article regarding the benefit/cost, networkability, and sustainability of HS/HC ATN systems:

Benefit/cost

While the use of off line stations allows smaller cars to be used, the benefit/cost ratio is not improved unless the control technology achieves a headway of 4.5 seconds or less at a speed in the range of 60 mph. This is not achievable using Moving Block control systems and more innovative approaches must be used.

If a headway of one second at 60 mph could be achieved, metro rail-like service can be achieved at about a quarter of the cost. This would result in four-fold improvement in benefit/cost.

Networkability

If higher line capacities at higher line speeds can be achieved, regional networks of PRT service lines would become possible and could, in concept, scale up indefinitely.



Sustainability

The use of small cars instead of long trains makes it possible to use sustainable forms of energy generation. Also, energy used per passenger-mile is approximately one third of that for other transit modes. This is probably due, in large measure, to the efficiencies resulting from the reduction in unoccupied seat miles noted earlier.

Figure 13 below summarizes these and other virtues of the ATN concept.

| Subject of Comparison | Conventional Rail | ATN/PRT |
|---|--|--|
| Benefit/Cost | Considered good, because new lines continue to be built | Better than conventional rail if the headway can be reduced below approximately 4.5 seconds at mainline speeds |
| Capacity | ~16,000 seated pphpd (BART capability) | Same if the headway can be reduced to approximately 1 sec at 60 mph |
| Networkability | No, because it is expensive to construct and operate large trains into densely populated communities | Yes, if low headways at high speeds can be achieved, many local track networks can be interconnected with high speed/high capacity lines to serve large areas with fleets of small cars that can run on both the local and interconnecting tracks. |
| Farebox Recovery | No | Yes, improved operating efficiency is likely to achieve subsidy-free operation |
| Viability of Using Sustainable Energy Sources | No | Yes, small cars require much lower levels of power for acceleration than trains |

Figure 13: Summary Comparison Matrix

CONCLUSION

Given the summary above, there is ample reason for the ATN/PRT concept to be promoted as more than a first/last mile mode of transport. But this would require the industry to embrace the control concepts that have now been pioneered by Transit Control Solutions.

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