ASCE APM05 Special Sessions on PRT

Infrastructure Cost Comparisons for PRT and APM

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Abstract

Physical parameters and costs have been compared for APM and PRT infrastructure. For APM systems published data on a variety of existing services has been used, supported by detailed evaluation of representative monorail and LRT installations. For PRT systems the analysis has been based on the ULTra PRT system, using results from the construction of the test track and from an in-depth costing exercise that has recently been completed. This has provided a robust basis for the comparisons.

APM vehicles are of far larger scale than PRT vehicles, which results in a larger scale of infrastructure. This is reflected in overall guideway weights for monorails which are three times those of PRT systems and for LRT around ten times PRT. The reduced scale of PRT systems has major benefits in installation flexibility. The relative increase in the scale of APM systems is suggested to be a key factor driving higher cost.

Guideway and station costs have been analysed for APM and PRT systems. Comparison between these results leads to the conclusion that on average; PRT infrastructure can be provided for a third the cost per mile of equivalent APM infrastructure, and PRT stations for at least half the cost of an APM station.

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1. Introduction

There is a growing interest in the use of Personal Rapid Transit (PRT) systems for a variety of public transport applications, at airports, in cities, in new developments and other special situations. Early PRT studies focussed on urban applications to demonstrate how PRT might provide the no wait, quiet, energy efficient, personal driverless taxi that would replace the private car. The benefits of PRT as a public transport system have been analysed by Lowson and others. The environmental and socio-economic implications of applications in four European cities have been evaluated in a recent European Commission study. These clearly demonstrate the potential of PRT to provide a cost effective alternative to cars for many urban trips.

A wide variety of papers have been published describing PRT and further papers will be given at the present conference. The best reference is the extensive website organised by Schneider. This provides full information on a wide variety of current and previous PRT projects as well as other forms of advanced transport.

PRT systems are a smaller scale version of conventional Automated People Movers (APM) which are now in wide spread use around the world. According to Fabian there are now 114 fully automatic people movers in operation, with another 15 under construction.

APM and PRT systems have many features which are similar. They are both systems featuring automatic vehicles running on segregated track, which may be at-grade, in tunnel, or elevated. Access to both is at a series of dedicated stations and both are most often proposed for use in dedicated applications. However the nature of the transport service offered differs significantly.

PRT systems offer transport on demand to small groups of passengers. Passengers only travel with chosen companions. Because PRT stations are off-line all travel is non-stop between origin and destination. Overall trip times by PRT are low, and a proportionately greater number of stations is practical.

In contrast, Automatic People Mover (APM) systems offer the same form of transport in principle as buses. They require gathering people together in groups, making them wait for service and restricting access to relatively few stations, which in turn increases the walk time required for the overall transfer. This also leads to large station size and pedestrian concentrations at station locations. Providing quicker access to an APM, as required for example in airport car park areas, would require frequent stops leading in turn to severely reduced average trip speed.

For low demand applications such as a car park, service is likely to be infrequent, at best 10 minute intervals, so that overall trip times including walk, wait and journey, are bound to be high. These issues are fundamental difficulties in any application of conventional corridor-collective transport.

Thus PRT systems offer basic benefits in transport effectiveness from the point of view of the passenger. Their small scale also results in useful advantages in terms of cost, and in particular infrastructure cost, as will be demonstrated in this paper.

A concern associated with many APM installations is the overall cost. Many recent APM systems have had reported overall capital costs exceeding $100 million per mile. The budgetary cost for the currently proposed system at Miami Airport, operating on a simple two way track 1.3 miles in length is $220 million. Jakes (2003) has suggested that these costs are unjustified, however these are costs which are being paid for recent installations.

The figures in Table 1 are taken from an analysis by Shen et al, but inflated to 2005 US dollars by use of the CPI (130.1 from Jan 1994 to Jan 2005, see also discussion in section 5.2).

Cost per Route Mile ($million 2005)			
	Low	Average	High
Rapid Rail Transit Systems	$110.5	$201.9	$293.8
Light Rail Transit Systems	$25.4	$88.8	$195.2
Urban APMs	$82.7	$113.9	$145.5
Airport APMs	$48.8	$131.1	$237.0

Table 1 - Costs of Various Line Haul Systems

It can be seen that in broad terms there are only modest differences between the costs of the various systems. The cost variations within a particular category of system are of the same order, arguably even greater, than the variation between categories. This suggests that valid comparisons could be made between PRT and any line haul system rather than specifically APM systems.

This suggests in turn that the basic cost drivers are common engineering issues rather than specific features of the technology. The high cost of APM, and other line haul systems, seems likely to be associated with their (comparatively) large size. PRT is a transport facility of a considerably smaller scale than such systems. Thus PRT offers potential for reducing the capital cost of a system in comparison with conventional APMs, whilst providing a like for like passenger capacity with reduced delay to individual travellers, and comparable reliability.

An automated system can be divided into three parts, the infrastructure, control system and vehicles. A report, FTA(1992), gave an analysis of a variety of APM systems. The average percentage cost breakdown from that analysis is shown in Table 2, which also shows variations in component part proportions between high and low ranges.

Component	Low	Average	High
Guideway	16	26.3	36
Stations	3	11.4	24
Maint. & Support Capabilities	2	5.1	8
Power and Utility	3	7.1	15
Vehicles	5	19.3	32
Command, Control & Communication	5	12.0	22
Engineering & Project Management	10	18.8	28

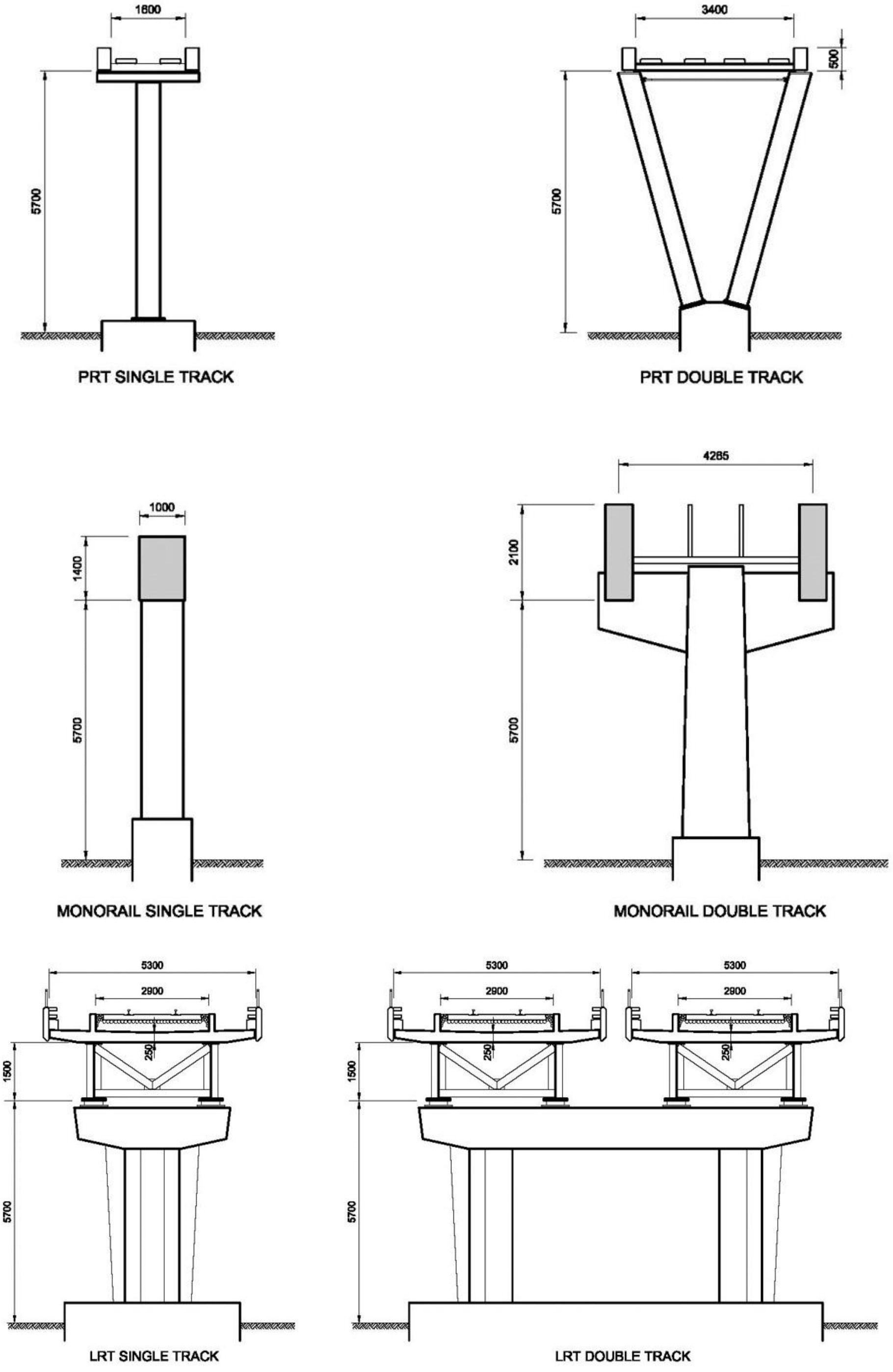
Table 2 - Percentage Breakdown of APM Costs

It can be seen that the total infrastructure costs, (Guideway, Stations and Maintenance and Support Capabilities) at 42.8%, represent more than half of the capital cost if project management is excluded. This finding is consistent with figures published by Warren and in a recent evaluation of the Seattle Green Line Monorail projection of costs. The guideway itself is the largest cost element of the infrastructure. Similar results apply for PRT systems. Typically the infrastructure costs for both APM and PRT systems dominate the cost comparisons. The infrastructure is also the system element which takes the longest to design and realise, and therefore the reduced scale of PRT should offer programme advantages.

The objective of the present paper is to provide a comparison of design features and costs of PRT infrastructure compared with conventional APM and line haul transit installations.

2. Basic Comparison of APM and PRT Infrastructure

A “small” scale APM system will use trains with gross weights of around 40 tonnes and generally a railway engineering approach to design. These require large-scale infrastructure, which is difficult to fit into a congested urban area or airport terminal. A comparison of APM and PRT infrastructure scale is provided in Figure 1. The PRT structure depicted is the ATS Ltd ULTra system as developed for its test site in Cardiff. Comparison is made with the infrastructure for the Las Vegas monorail, the Sydney monorail, and the Kuala Lumpur LRT.



PRT SINGLE TRACK

PRT DOUBLE TRACK

MONORAIL SINGLE TRACK

MONORAIL DOUBLE TRACK

LRT SINGLE TRACK

LRT DOUBLE TRACK

Figure 1 Typical APM and PRT Infrastructure

APM and PRT infrastructure have recognisably common elements, especially for elevated construction, as the guideway is supported from a series of columns. This also applies to monorail systems and is applicable for single and double track systems.. A comparison from the projects illustrated in Figure 1 is shown in Table 3.

Comparison of Principal Dimensions of Single Track Structures			
	PRT (ULTra)	Monorail (Sydney)	Light Rail (KL LRT)
Width (mm)	2100	1000 (est.)	5300
Depth (mm)	450	1400 (est.)	1750
Column (mm)	500 (diameter)	914 UB (est.)	2400
Span (m)	18	24	25
Comparison of Principal Dimensions of Double Track Structures			
	PRT (ULTra)	Monorail (Las Vegas)	Light Rail (KL LRT)
Width (mm)	4000	4265 (est.)	11100
Depth (mm)	500	2100 (est.)	1750
Column (mm)	2 x 500	1500 (est.)	2 x 1700
Span (m)	18	25 (est.)	25

Table 3 - Basic Size Comparisons

The PRT structure shown here has been designed from first principles to meet the requirement of the PRT system. The design has a high span to depth ratio of 40, which has additional benefits in reducing visual intrusion. The elevated structure is overall of lower size and weight than the equivalent footbridge. Indeed the PRT structure would be not be satisfactory as a foot bridge as these have to accept pedestrian crowd loads, normally required to be around 500kg/m^2, which are considerably higher than the load imposed by the PRT vehicles of 200kg/m^2.

This reduction on load from the PRT system leads to further benefits. For example the 200 kg/m^2 design load is well below the level required for floor live load in building codes. This means that PRT systems can be run into buildings with no requirement for any strengthening of basic structure.

These differences in size from APM to PRT also lead to significant differences in load transferred to the supporting ground. The actual loads on the ULTra column structures are 10 tonnes. This compares with a typical APM column load of 80-100 tonnes. This difference results in smaller ground works and has further implications in relation to service diversions. The small scale and load of the PRT columns compared to the APM requirements means that simple solutions to service intercept problems will frequently be possible, for example local sheathing or straddling of the service line.

The overall scale comparison has significant benefits in operational flexibility. Work by Muller (Ref) and the analysis from Table 3 above shows that two PRT lines can be fitted into half of the cross sectional area required for a full APM system. Similar results were reported by Lowson in a PRT application for Heathrow.

3. Comparison of Materials Utilised in Construction

3.1 General

The preceding discussion has focussed on descriptive information concerning the comparison between PRT and APM systems and a general understanding of the difference in scale between the two systems. This can be taken to a greater level of detail by examining the actual quantity of materials used in construction. Such measures are readily compared without the need to make adjustments for local procurement or construction market effects. The comparison results in measures for steel and concrete materials, to some extent these are interchangeable, and can be added as weights to give a general comparison.

3.2 The ULTra PRT system

For the purposes of this discussion reference is made to the design drawings for the ATS Ltd ULTra system. The scale of the guideway structure was introduced in section 2. A standard based on an 18m span has been adopted and is described here. This is the element which is in service on the test track and which was evaluated for the Cardiff network. Designs have been made for longer spans, an earthquake tolerant column cross head, and special "gateway" structures, but these are not included in this discussion.

Photograph 1 - Cardiff Test Track

The structure is made up from columns, longitudinal spanning side beams and cross members all in standard rolled steel sections. The running surface for the rubber tyred vehicles is constructed from precast concrete planks some 95mm thick with nominal reinforcement. The foundations require a base plate to anchor the column, and a pad to spread loads to be compatible with soil support capacity. In some situations soils will not provide reliable support and a piled foundation to "rock" might be required. This is a very site specific requirement and may vary along a network, and is not part of this discussion. An APM in similar ground would require deeper support earlier in the soil capacity spectrum, as column loads are typically many times greater.

Dealing with the ULTra superstructure alone, i.e. excluding columns and foundations, and based on the standard 18m span, gives the following measures:

- 2.5kN/m of steel work
- 2.1kN/m of concrete
- Total weight of superstructure is 4.6kN/m (0.46 tonnes/m)

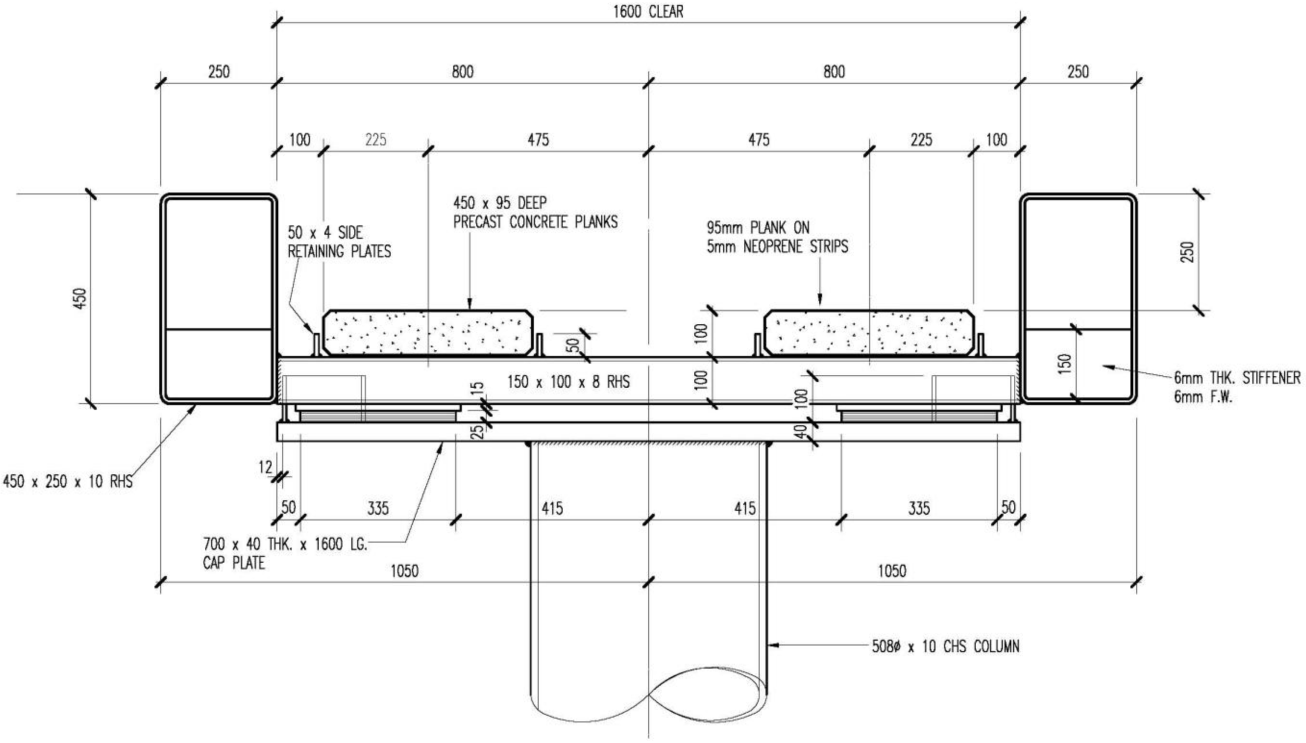


Figure 2 PRT Section for 18m span

3.3 APM Comparator

Published information often does not clearly identify the materials for infrastructure in operating APM systems. For the purposes of this discussion, reference is made to the Kuala Lumpur LRT structures which carry similar loads and for which a similar span between columns has been utilised. This is a single track viaduct supporting ballasted track with maintenance access walkways both sides. The total width of the viaduct is some 5.30m. The composite steel concrete construction was delivered through a design build procurement programme and each element has been designed to work to code limits. Steel sections and weights vary along the length and in summary steel beams and cross bracing which form the lower superstructure over a representative 257m length, amount to some 2305 kN of steel giving an average of 8.98kN/m.

Photograph 2 - Kuala Lumpur LRT

The concrete deck is some 1.45sqm in section, heavily reinforced, to give an average of 36.3kN/m

The total weight of the superstructure therefore is some 45.3kN/m (4.53 tonnes/m).

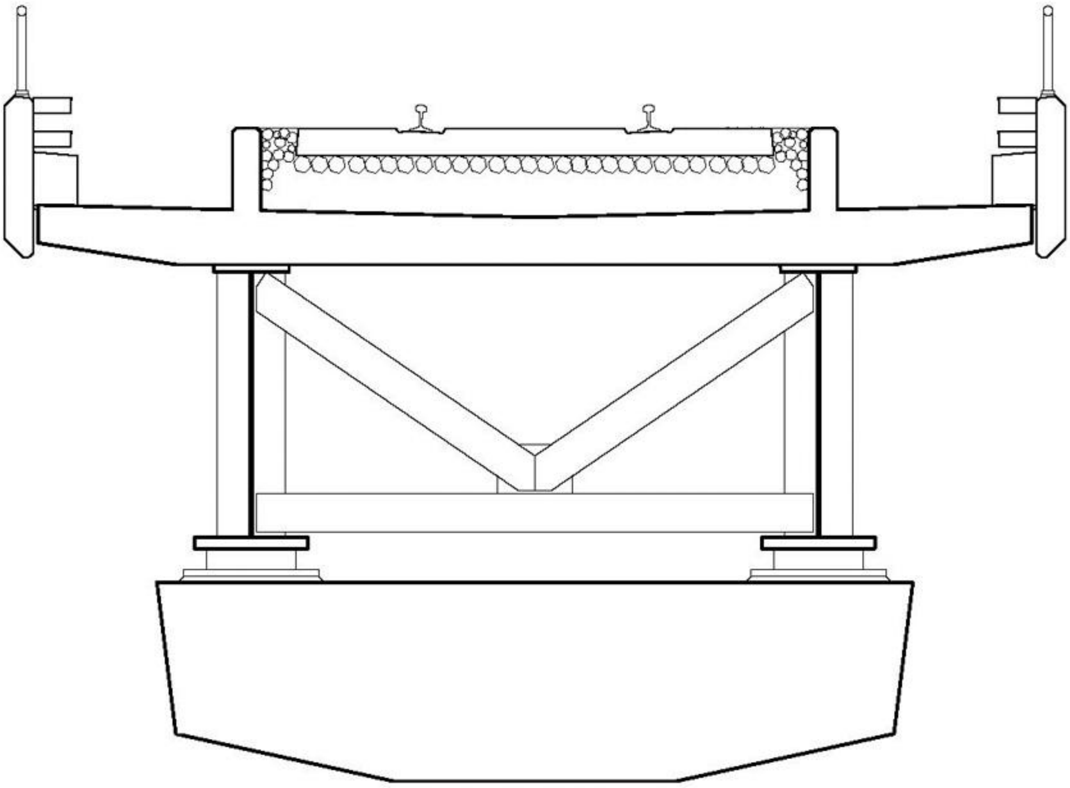


Figure 3 LRT Section for 24m span

3.4 Monorail comparator

Monorail systems have the potential to offer reduced infrastructure amongst APM and independent guideway transit systems, as the single beam sits over the supporting columns and cross heads are not normally required. From amongst the systems in operation for which information can been accessed the Sydney Darling Harbour installation appears to be the lightest infrastructure of any. It also has the advantage of being located in publicly accessible area from which it is possible to make a reasonably reliable estimate of the structural dimensions. The standard span of the carrying beam is 24m and is supported on Universal Columns of dimension 700 x 900mm. The overhead beam is a box some 1400mm deep and 1000mm wide. In order to support the load of the trains and resist buckling the box section should have at least 20mm thick webs and 60mm thick top and bottom flanges. This indicates a steel section of at least **171200**mm^2 which would have a weight of some **13.5**kN/m (1.35 tonnes/m).

Photograph 3 - Sydney Monorail

No other monorail system has been identified which works on such a small infrastructure with a single direction looped track. The recent systems installed in Las Vegas and Kuala Lumpur are generally double track, in concrete construction and incorporating a deeper beam.

3.5 Columns and Foundations Comparison

A similar comparison can be made amongst the substructure elements. The column for the ULTra standard span is some 500m diameter rolled hollow section with a wall thickness of 10mm. This in standard application is 5.7m high to provide clearance above highways.

The comparable LRT column is some 2000m by 1000mm in reinforced concrete.

The Sydney monorail column is comparable to the ULTra column

The foundation requirement at any column is a function of the vertical and rotational loads to be supported and the bearing capacity of soils. It is known that the ULTra columns on straight track have to support a vertical load made up from the weight of the superstructure and potentially 6 cars at 1200kg each. This gives a column load, which transfers to foundations, of approximately 165kN.

By the same analysis an APM column might be required to carry a vertical load of the superstructure, and a proportion of a train set estimated at 50kN/m. This gives a potential column load of 2400kN (using the KL LRT figures) from which it can be seen that the foundations would need to be significantly larger than for the comparable ULTra PRT column.

3.6 Summary of Weight Comparison

In the preceding paragraphs the weights of materials which comprise the principal guideway component (the beam or track support superstructure) has been analysed from design drawings and direct observation. The results are summarised in Figure 4.

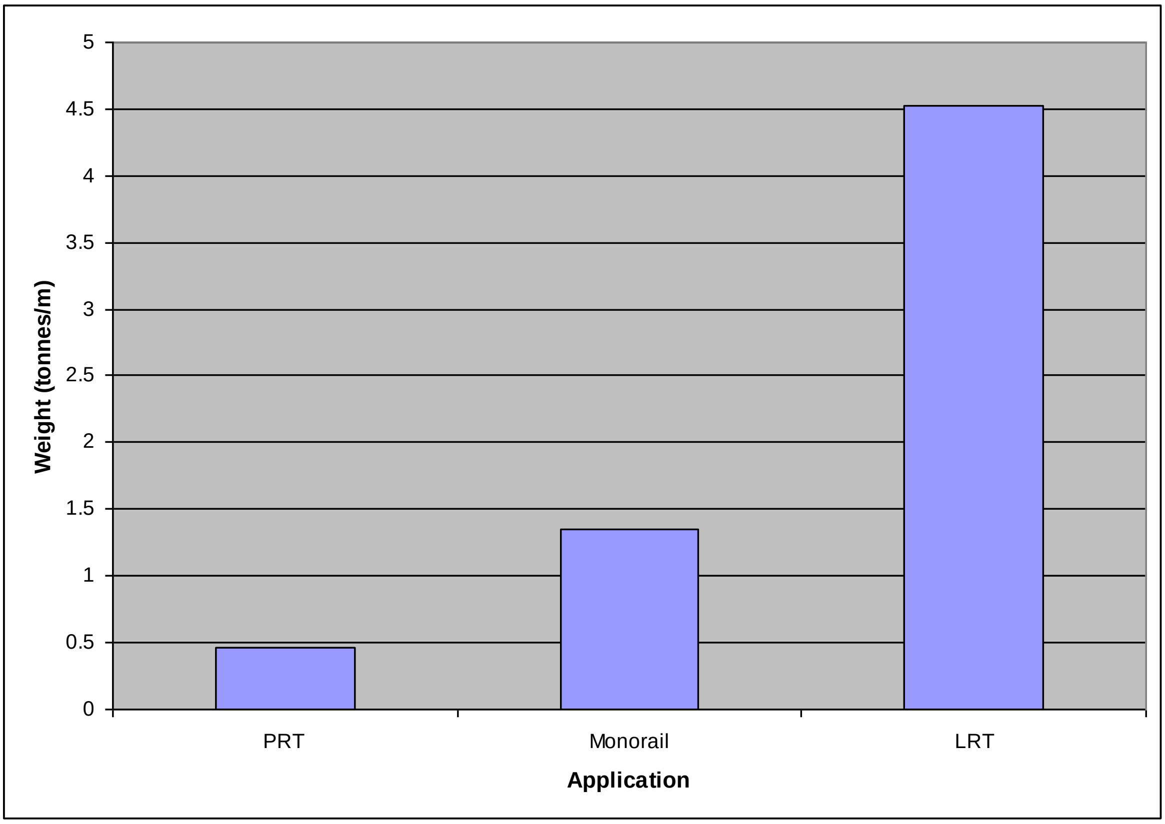


Figure 4 - Comparison of Superstructure Weights – Single Track

This analysis shows that the comparison between superstructure weights for PRT and a very small scale monorail system is a ratio of 3. The comparison between PRT and conventional line haul LRT is a ratio of 10.

This comparison shows that PRT has the potential to provide a transit facility for which the weight of materials used in construction would be significantly smaller than for comparable alternative line haul transit systems.

4. Installation Flexibility

4.1 General

There are two aspects to flexibility; the ability to fit within the demanding space constraints typical for example of an airport, and the ability for reconfiguration after installation. Flexibility is an important issue in many developments. All airports have undergone extensive and extended growth, which can be expected to continue for some time into the future. Thus the flexibility to easily reconfigure a transport system to meet new needs is an important aspect.

Installation of new APM systems has proven to be a difficult task taking extended time. The installation of the Las Vegas Monorail was a comparatively straightforward installation by APM standards. In this case the time taken from ground breaking in Aug 2001 to initial operation of the 3.9 mile track in July 2004 was just under three years. In other contexts, notably airports and historic city centres, the small space available makes installation of heavy structures complex and expensive.

The disturbance to operations caused by major rebuilding programs is a fact of life for most applications, but nevertheless remains a major issue and is a significant negative factor for larger scale APM systems. By comparison disruption caused by PRT is minimal. This is due to the far smaller scale of the infrastructure which can be largely prefabricated as modules off-site. Although some small scale ground works are inevitable the infrastructure as a whole can be installed in months. PRT offers the opportunity to alter column spacing with the same superstructure to overcome local ground features such as services footways and roadways, and can operate on smaller radius curves such that fitting into existing built environments is more readily achieved. The modular construction also allows elements to be removed and replaced within a short time (such as overnight) as part of route modification or extension.

4.2 Test Track Experience

ATS Ltd has constructed two test tracks:

- Avonmouth: a flat, wide tarmac straight with turning circles at both ends used for basic vehicle performance testing.

- Cardiff: a ‘figure of eight’ test track nearly 1 km long with all the features expected in a typical application (except for a tunnel). Features include guideway at grade and elevation, merges, diverges, inclines, declines, a variety of unbanked and banked curves, a station and manoeuvring surfaces for detailed control trials.

The Avonmouth test track was completed in May 2001 and the Cardiff test track in August 2001.

Photograph 4 - Aerial view of Cardiff test track

The Cardiff test track was designed in outline and specified by ATS Ltd with the detail design being completed by Ove Arup & Partners who also undertook the project management of the construction of the track on behalf of ATS. At grade the guideway is a simple concrete running surface with kerbs 250 mm high. At elevation the guideway side members are standard rolled hollow sections 450 mm deep with steel cross members supporting the two reinforced concrete running surfaces. The elevated (bridge) sections were fabricated off site and transported on standard highway licensed vehicles. The modular design of the overhead section is patented jointly by ATS and Arup. The overhead section of the test track comprises three standard 18m spans supported by steel columns.

A key achievement was the erection of the complete three span elevated section in an elapsed time of under four hours (measured from the prepared concrete foundations to the point where a vehicle could be driven over the elevated section). ATS is therefore confident that, where required, the elevated guideway sections can be erected during short access periods, thereby minimising disruption to existing operations.

Photograph 5 - Elevated superstructure waiting to be lifted into position

Photograph 6 - Lifting in the elevated sections

Photograph 7 - Completed bridge

Construction sequence of the Cardiff test track elevated section.

Both of the test tracks were completed to time and budget, giving ATS confidence in the practicability of modular build concepts, and in the projected costs and timescales associated with real applications.

The modular design concept has been extended to curved sections and merge / diverge turnouts. These too can be manufactured off site and transported on standard road vehicles to site for simple final assembly and installation.

5. Infrastructure Cost Comparisons

5.1 General

For the purposes of this discussion "Infrastructure" is taken to be all of the works constructed by a civil engineering contractor. The Infrastructure therefore excludes land and land rights costs, vehicles, power supply and distribution, and control systems, but includes the building works for stations and depots as well as the guideway. The guideway element is then further subdivided into foundations, columns and superstructure. These definitions are consistent with the breakdown in Table 2.

This section of the discussion provides comparative data on the projected infrastructure cost of APMs and PRT. PRT costs are based on the ULTra system, the costs of which have been analysed in depth. These costs originated from the building of the prototype test track, and re-evaluated by contractors for an urban network. For APMs use has been made of the comparative data originally published on Automated Guided Transit by the FTA in 1992 and extended by reference to more recent projects.

5.2 PRT Infrastructure Costs

The ULTra prototype track includes both at grade and elevated sections together with merge diverge elements and a station. A recent in depth costing exercise has been undertaken involving a full specification document based on a number of complete track designs for installation in Cardiff. These included at-grade and elevated track, with straight and curved sections, and both at-grade and elevated stations and all other infrastructure elements of a complete installation. This work was developed under instructions from Cardiff County Council (the city transit authority), and as part of the European Commission four city EDICT study into urban applications of PRT systems.

The system costed in this exercise comprised 19.8 km of guideway, 17.7 km of it elevated, with 22 stations and 2 depots. All components and materials were to the ULTra standard design and the specification provided to the contractors was based on experience gained from the design and construction of the Cardiff Bay test track, and subsequent design reviews. The contractors' estimates, compared with the ULTra engineering consultant's independent estimate for the set of measured work items were as follows:

Contractor A	Contractor B	Contractor Mean	Consultant
£18.9m	£26.7m	£22.8m	£39.1m

Table 4 - Works cost estimates

Estimates from contractor A were consistently lower than those of Contractor B for each individual part and stage. In the four months between receiving a price from Contractor A until that from Contractor B the price of steel in the UK had risen significantly, but not sufficiently to explain the difference. Contractor B had been responsible for the construction of the test track so may have brought a greater depth of understanding of the risks to the estimate.

The estimate was then extended by adding allowances for contractor profit and overheads, services diversions, foundations in various ground conditions, design and legal fees and contingency to give a more realistic estimate of the potential construction out turn cost. The same comparison of the three estimates is as follows:

Contractor A	Contractor B	Contractor Mean	Consultant
£33.1m	£43.9m	£38.5m	£58.0m

Table 5 - Total cost estimates

The specification did not include for mechanical or electrical equipment, vehicles or power and controls, and therefore the reported costs relate only to civil engineering works. Further analysis of the prices shows that the majority of the difference is in the pricing for elevated structures, where the consultant's estimate was between 2 and 3 times the contractor's prices for this work. In preparing the estimate a judgement had to be made concerning the additional cost of installation above congested urban streets where access may be limited to short night time periods and where extensive traffic management measures may be required. It is clear that the consultant took a very cautious view of the implications of these factors.

The results of this analysis provide a basis for cost projections and are believed to be robust, and for the purpose of comparison the Consultant estimate with all overhead factors included has been adopted. This projection allows for a significant proportion of the guideway being elevated which is appropriate for urban applications.

The cost in US$ per mile of all civil engineering works for guideway, stations and maintenance depots, has been calculated by the application of the following factors:

Total infrastructure cost	£UK 58.0m
Cost per km (for 19.8 km system)	£UK 2.9m
Cost per mile (at 1 mile = 1.609km)	£UK 4.7m
Cost per mile (at 1US$ = 1.85 £UK)	$US 8.7m

The overall cost of the PRT track and associated civil engineering works, for typical installations is found to average $8.7 million per mile.

The cost of the guideway alone is a proportion of the figure derived above, and analysis of figures show this cost to be £44.9m for the whole network evaluated. By the application of the ratio of guideway to total civil engineering (infrastructure) cost the relevant rate for guideway alone can be determined. This is found to be £2.27m per km and by the application of the same conversion factors used above, gives US$6.75m per mile in 2004 prices. It should be noted that this represents a very robust estimate and some 50% higher than a contractor estimate for the same scope of work. A more realistic conclusion might be to consider a range from $4.5m to $6.75m per mile for PRT guideway.

5.3 PRT Station Costs

As noted a full evaluation of station costs has also been undertaken. Since PRT stations are significantly smaller than APM stations, costs would be expected to be considerably lower. The projected average cost of elevated PRT stations including all equipment such as lifts, but without system management and control elements, has been derived from the same process described above by submitting outline designs to two contractors as well as having an estimate prepared by the design consultant. A much simpler station than described in the pricing documents has been incorporated into the test track facility and the contractors had less experience on which to base their estimates therefore the results are included with less confidence of their reliability.

Total budget allowance for stations	£10.5m
Number of stations	22
Average Unit price per station	£0.48m
Station cost in US$ (2004)	$0.89m

In some cases it will be possible to construct the PRT stations within an existing building and will reduce costs considerably. It should be noted that PRT station costs include for the station deck, the off line section of track and entry and exit turnouts.

5.4 APM Guideway Infrastructure Costs

A report published by the FTA in 1992 included a detailed comparison of the cost makeup of a number of APM systems. This report remains the best source of comparative data. Figures were given uniformly in US1990$. For the present purposes the APM costs reported in the FTA report will be updated to 2005 values by use of the US Consumer Price Index (CPI) inflation figures. The official CPI inflation between Jan 1990 and Jan 2005 is 149.7%.

Many questions can be raised about the use of indices for these purposes. First, there are several commonly used indices, including GDP deflators and Producer Price Indices (PPI). Both PPI and CPI are divided into product or industry segments and it is possible to argue that a particular segment index should be taken.

A second, and possibly more significant, issue is the phenomenon of specification creep. APMs built to modern practices will have differences in many respects from those built 30 years ago. An example is the universal use today of station doors, compared to partial use in earlier APMs. Many other aspects of the design will have been affected by new regulations which will have affected cost. Any projection from old to present day cost must be subject to large error margins. Nevertheless inflation is a fundamental feature of all prices and use of the CPI provides a plausible, albeit flawed, method to update old figures to modern values

The FTA data has been analysed to provide key information on infrastructure costs. A listing of all relevant data, adjusted to $2005 as noted, is presented in Table 6. These guideway costs should be directly comparable with those for PRT derived in section 5.2.

Location	**Year**	**Application**		**Length**	**Guideway Costs**	**Guideway Costs**	**Station Costs**
				Miles	$m (2005)	$m/mile (2005)	$m (2005)
Atlanta Airport	1980	Airport	Under-ground	2.29	41.8	18.2	2.2
Busch Gardens	1975	Theme Park	Elevated/ At-Grade	1.33	5.1	3.9	0.2
Dallas /Fort Worth Airtrans	1974	Airport Center	Elevated/ At-Grade	12.80	38.5	3.0	1.5
Denver Airport	1993	Airport	Under-ground	1.85	18.7	10.1	0.9
Duke	1980	University Medical Center	Elevated/ At-Grade/	0.56	4.9	8.8	0.5
Fairlane	1976	Shopping Center	Elevated	0.49	6.2	12.7	0.6
Houston	1981	Airport	Under-ground	1.37	17.4	12.7	1.2
Las Colinas	1989	Urban Business Center	Elevated	0.74	8.2	11.1	0.7
Miami Airport	1980	Airport	Elevated	0.51	7.3	14.4	4.0
Morgantown	1975	University	Elevated/ At-Grade	8.60	80.4	9.4	2.9
Orlando Airport	1981	Airport	Elevated	1.47	11.5	7.8	2.3
Sea-Tac	1973	Airport	Under-ground	1.70	37.0	21.7	2.8
Tampa Airport	1971	Airport	Elevated	1.35	10.3	7.6	0.8
Tampa Parking Garage	1991	Airport Parking Garage	Elevated/ At-grade	0.51	4.2	8.3	0.1
Average				2.54	20.8	10.7	1.5

Table 6 - APM Infrastructure Costs from FTA (1992) in $m 2005

Generally there appears to be no strong trend of cost per mile with track length. Any such effect in the present data is small. Some commentators (e.g. Jakes) have suggested that airport applications involve additional costs. The average figures from the present data are $8.2m/mile for the airport applications and $9.0m/mile for the non-airport, but $15.7m/mile for the underground. Perhaps surprisingly, airport costs per mile are around 10% lower than the non-airport. This may be partly explained by the shorter average length of the non-airport applications. The doubling of cost for underground track is not unexpected. Indeed it is widely suggested that underground track will be three times the cost of elevated. In the present data it may be difficult to report full underground data since much of the cost of the underground structure is likely to have been absorbed in other parts of the overall building or project costs. Similarly there is no trend of price in relation to date of original construction. It must be accepted therefore that local and specific features influence cost and that significant variation from project to project should be expected. Although some of the applications have sections which are in part at-grade, in nearly all cases such sections are a small proportion of the total and this has been ignored.

The APM guideway figures have been plotted to show the trend cost line from lowest to highest The trend shows significant clustering around the mean value for all scores of $10.7m/mile The inclusion of the extreme values which, at the upper end are known to reflect underground guideway, has little effect on the mean taken forward into the comparison, which is primarily based on elevated structures.

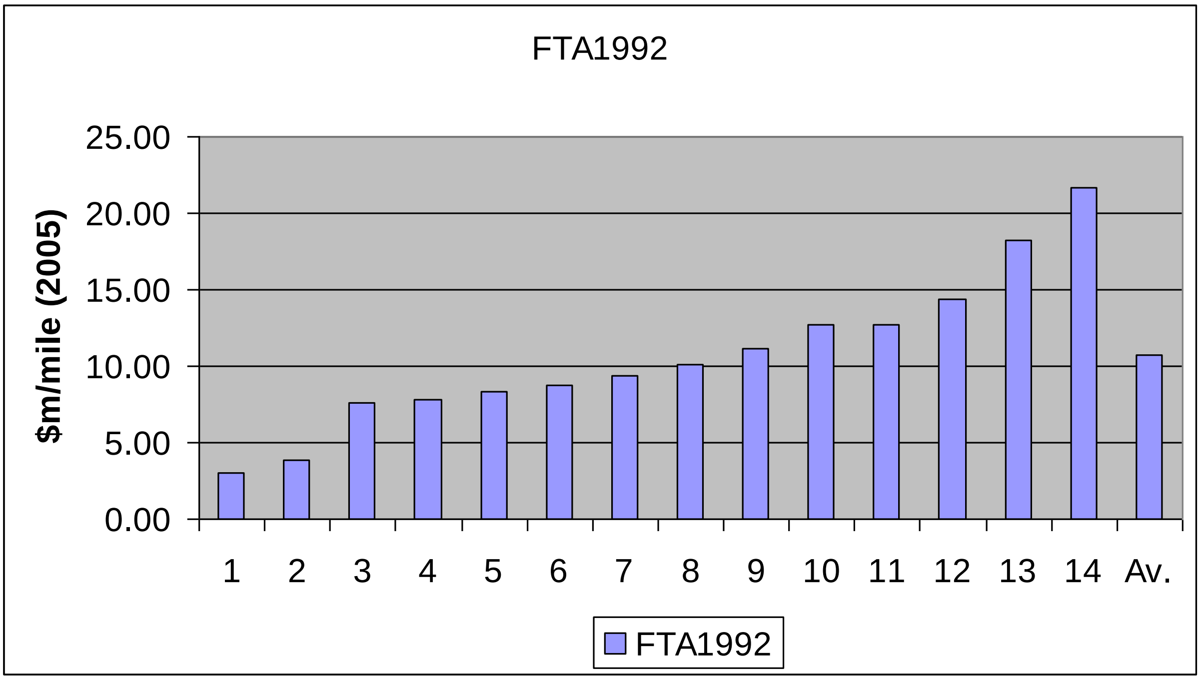


Figure 6 - Guideway cost by project $/mile

Other APM system costs have been reported but not with the same clear breakdown into the component parts. In Section 1 a means of estimating the guideway cost from the total project cost was set out. By the application of this factor to reported project costs, further indications of the APM guideway costs can be derived. These have been taken for Kuala Lumpur, Las Vegas and Seattle monorail reports, and the selection of projects reported by Shen. The calculation is set out in Table 7. These additional factored project costs have been added to the histogram from which it can be seen that the more recent projects indicate a trend of higher guideway costs.

System	Year	Application	Length	Length	Capital Cost	Capital Cost	Guideway Cost
			km	miles	$m/miles (1994)	$m/miles (2005)	$m/miles (2005)
Lille VAL	1983-89	Urban At grade	25.3	15.8	105.8	137.5	36.2
Vancouver Sky Train	1986-94	Urban Elevated	28.8	18.0	63.4	82.7	21.8
London DLR	1987-93	Urban Elevated	27.0	16.9	68.7	89.6	23.6
Miami Metromover	1986-94		7.1	4.4	111.5	145.4	38.2
Paris APM	1996	Airport	4.3	2.7	37.3	48.6	12.8
Denver APM	1995	Airport Tunnel	2.9	1.8	82.7	107.8	28.4
Newark APM	1995	Airport Elevated	3.1	1.9	181.6	236.9	62.3
Seattle Monorail	2004	Urban Elevated		14	x	89.0	23.4
KL Monorail	2004	Urban Elevated		5.3	x	59.0	15.5
Las Vegas Monorail	2004	Urban Elevated		3.1	x	109.0	28.7
Average						110.6	29.1

Table 7 - Other Guideway Costs

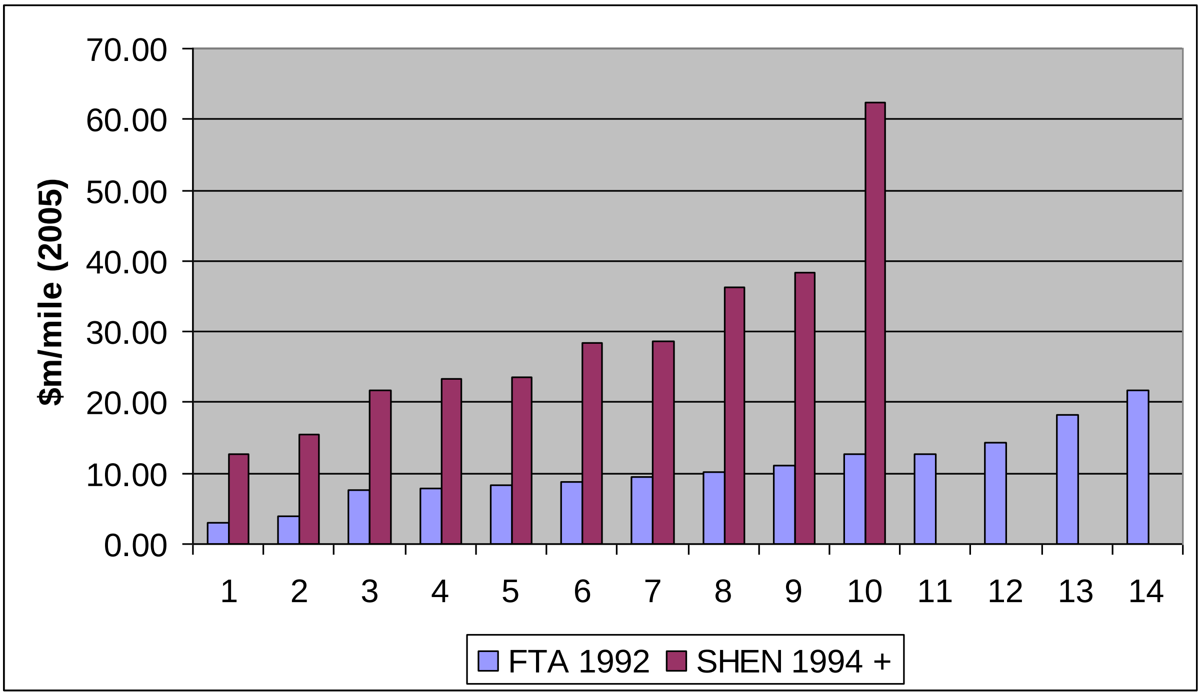


Figure 7 - Guideway cost by project $/mile

The variation between project results can be explained by differences in technology, location of the guideway, (at grade, elevated, in tunnel), single or double track, economic conditions at time of procurement, procurement method, and others have suggested, extent of competition.

As a rule it might be expected that a range of 6 should occur between project costs, three being the general range between at grade and tunnel construction cost, and then factored by single or double track. In these figures the range is from $3.0m / mile to $62.3m / mile, a multiplier of around 21. By omitting the extreme upper value (Newark APM) the ratio of the range reduces to 13, which is closer to predicted, and this gives considerable confidence to any comparison made.

The average of the 14 FTA results is $10.7m/mile. The average of the 10 additional projects (Shen etc) is $29.1m/mile reducing to $25.4m/mile if Newark is excluded. This indicates an overall average for 23 projects (excluding Newark) of $16.4m/mile.

5.5 APM Station Costs

Stations are the second key part of infrastructure. Figure 8 gives a plot for station cost against track length using data from Table 6. Here there is some expectation that larger track length would lead to larger stations. There is good evidence that patronage levels will increase for longer tracks, because the system will access a larger number of people.

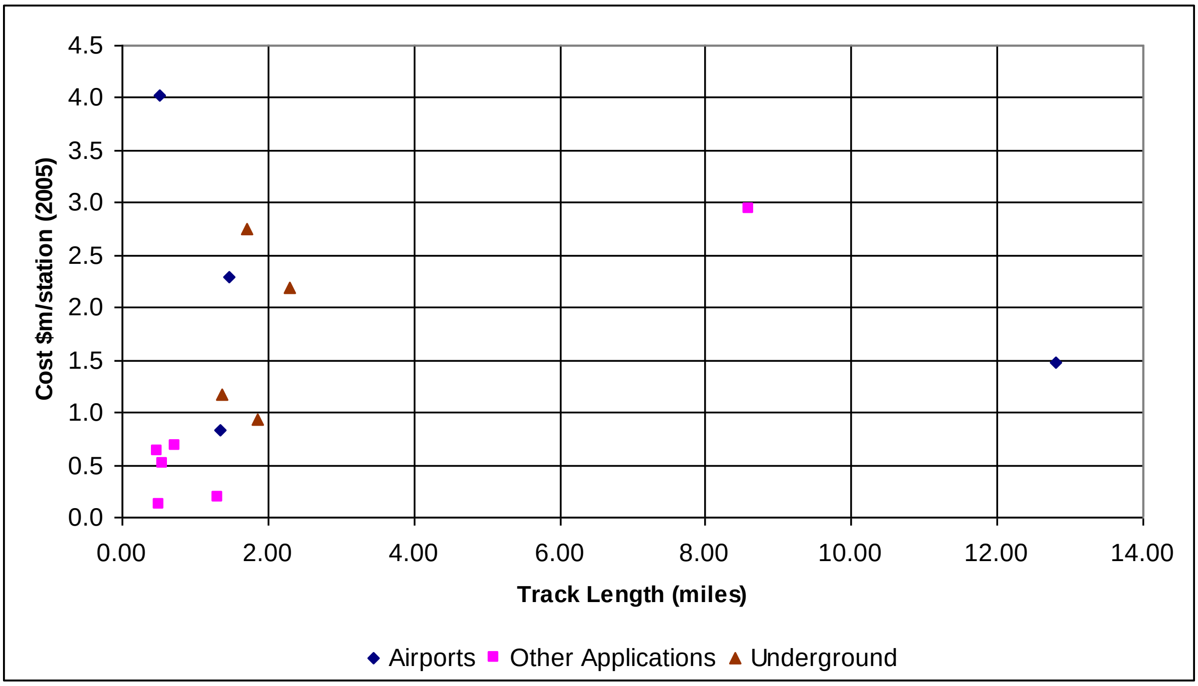


Figure 8 - Station Cost in $m (2005) against track length

It can be seen in Figure 8 that station costs do demonstrate an increase with track length. However the obvious point in the figure is that all the short length systems with low station costs are non-airport. Surprisingly, there is no evidence that underground stations are any more expensive than elevated stations. It is suggested this will be due to the nature of the contracts let, where the key underground structure will have been formed as part of an overall construction contract before handover to the transport installer. The actual average figures are $2.0m per station for airport applications (including underground) and $0.8m for non-airport applications, a 150% increase for the airport case. Some of this will be due to the greater route lengths and higher patronage, and some to the attention which airports give to the quality of the environment, compared with urban transport operators. The average of all results is $1.5m per station.

Photograph 8 - Kuala Lumpur LRT Station

Application of the station proportion to the 10 additional projects identified in Table 7 does not provide a useful comparative value as the number of stations in each system has not been reported in sufficient detail to establish a unit station cost.

5.6 Comparison PRT / APM Costs

It is recognised that each project has unique characteristics which influence cost. These may be a function of the application, the site and ground conditions, the selected technology, the means of procurement, the sources of funding and other factors. In the preceding analysis some effort has been put into abstracting from published historic data a reliable guideway cost for a selection of APM projects. These results exhibit considerable variation between the costs identified from the 1990 FTA group, within the costs for the selected later projects and across the whole range of projects analysed. The central 23 projects (identified by omitting the extreme value at the upper end of the overall range) have a median value of $12.8m/mile and a mean value of $16.4m/mile. The comparable median and mean for the entire set of 24 values are $13.6m/mile and £18.4m/mile, showing that the use of an average result from the data is hardly distorted by the extreme upper value.

However they all demonstrate higher costs than for PRT guideway. The difference is in the order of approximately a factor of 2 for the FTA results and at least a factor of 4 for the more recent projects. Overall the ratio of PRT/APM guideway cost would appear to be in the order of 3. The comparison is consistent with the weight comparison made in section 3.

By the same process the ratio of PRT/APM station costs would appear to be in the order of 2 for stand alone applications. The observation in section 5.3, that the PRT station costs include sections of off line track and turnouts should be examined to refine this comparison.

6 Summary and Conclusion

There is an increasing interest in applications for PRT in situations where larger APM systems present challenges of scale, integration, service provision or cost. Comparisons between options and performance characteristics of the PRT option would be part of any project evaluation. There are now around 115 operating APM systems in the world from which performance and cost characteristics have been measured, analysed and reported.

Depending on definition there is perhaps one PRT system in operation at Morgantown built in the mid 1970s. Modern PRT systems utilise more sophisticated management and control equipment, and generally require a smaller infrastructure. The ATS Ltd ULTra system is well advanced in terms of prototype development, and operational experience with public passengers on its test track in Cardiff. The construction of the test track and subsequent Cardiff County Council and European Commission funded evaluation of costs and benefits over a range of social, environmental, transport and construction issues for an urban network has created a body of information concerning the implementation of this PRT system. The information gained from test track construction and these studies has been used to compare the cost of infrastructure for PRT with that for APM systems.

The first comparison is between the scale of cars. ULTra incorporates a 4 person cab with a maximum laden weight of 1.2 tonnes. APM uses a range of vehicles for 2 to 9 car trains carrying several hundred passengers, and with a maximum weight orders of magnitude larger than for PRT.

The second comparison is between the weight of material utilised in construction of an elevated guideway alone. The comparable results are as follows:

PRT (ULTra)	**Combined weight guideway**	**4.6kN/m (0.46tonnes/m)**
Monorail (Sydney)	**Steel guideway beam**	**13.5kN/m (1.35tonnes/m)**
LRT (KL)	**Combined weight guideway**	**45.3kN/m(4.53 tonnes/m)**

These comparisons indicate that PRT guideway is a factor of at least 3 lighter than the lightest APM guideway identified, and a factor of 10 lighter than traditional line haul LRT.

The consequence of the overall lighter cars and structure is also reflected in columns, foundations and stations for PRT being significantly lighter.

The third comparison made is between the cost of infrastructure. Detailed layouts and specifications for ULTra have been exposed to contractor pricing to give a system civil engineering cost of US$8.7m/mile using the most pessimistic estimates. The same data indicates that the cost of the guideway element should be in the range US$4.5m to US$ 6.75m per mile, and the station cost around US$0.89m each.

Analysis of a range of APM systems either built or in detailed appraisal stage indicates an average guideway cost of US$18.4m/mile, and station costs of US$1.5m each.

Comparison between these results leads to the conclusion that on average:
PRT infrastructure can be provided for at least a third the cost per mile of equivalent APM systems, and PRT stations for half the cost of an APM station.

The range of APM infrastructure and station costs vary and these ratios apply to average figures, taken from a range of built or planned schemes. At the lower end of the range these figures indicate equality between APM and PRT costs. At the upper end of the range the APM infrastructure cost has been shown to be seven times greater than for a structurally equivalent PRT system.

Further work is required to demonstrate that the comparisons derived in this discussion apply for PRT and APM facilities providing similar capacity in terms of passenger movements and a similar level of service with common construction factors taken into account.

Acknowledgement

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