Personal Automated Transportation:

Status and Potential of Personal Rapid Transit

Technology Evaluation

January 2003

by the Advanced Transit Association

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NOTE: This report is published in a group of documents. Other documents in the group include an executive summary, a discussion and rationale for PRT, technology primer, FAQ, and other supporting reports.

The full set is detailed on the web site: www.advancedtransit.org/pub/2002/prt

Contents

Purpose

The purposes of this section of the report are:

- to compare and evaluate the specific systems that in a substantial engineering process,
- to arrive at some conclusions about which systems are ready, and what the remaining problems and challenges may be,
- to conclude whether deployment of any of the systems is recommended,
- to explain the technical components and design aspects of PRT systems in general,
- and to produce a framework for ongoing evaluation by ATRA.

In order to evaluate systems, there must be some assumed goals and criteria against which to evaluate. It is assumed that the goals of the potential customer are the same as those proposed elsewhere in this report, which are basically to provide transit with service characteristics that rival the automobile, at less cost, greater safety, greater equity, and lower environmental impact.

The specific evaluation criteria for system components are laid out at the beginning of each sub-section.

Study process

Each of the vendors below was contacted and asked to participate in the study by answering 19 questions in writing about their systems. In addition, an open invitation was sent to two internet listserves – transit-alternatives, and alt-transp.

System Name	Partic-ipated in study?	Contact Person, email, web address	Postal address, Phone (USA unless otherwise noted)
Austrans	yes	Nadia Savage or Gerald Ryan Nadia.Savage@aebishop.com http://www.aebishop.com	Australia Tel: +61-2-9805 8036
Autran	yes	Van Metre Lund autrancorp@att.net http://www.autrancorp.com	Autran Corp. 9220 E. Prairie Rd. #410 Evanston, Il 60203 Tel: 847 674 2407
Cabintaxi	no	Marsden Burger cabintaxicorp@msn.com http://faculty.washington.edu /~jbs/itrans/cabin.htm	Cabintaxi Corporation 1703 Parker, Detroit, MI 48214 Tel: 313-921-3955
CULOR	no	Jon Bogle bogle@lycoming.edu http://www.lycoming.edu /dept/art/bogle/culor.html	Jon Bogle Box 147 Lycoming College Williamsport, PA 17701
Cybertran	yes	Dr. John A. Dearien jad@cybertran.com http://www.cybertran.com/	CyberTran International, Inc 1800 Orion St., Suite 111 Alameda, CA 94501 Tel: 510 864 3221
FlexiTrain	no	unknown info@camdek.com http://www.camdek.com	
Frog, 2getthere[1]	yes	Robbert Lohmann robbert@frog.nl http://www.frog.nl	Frog Navigation Systems B.V. Cartesiusweg 120 3534 BD UTRECHT the Netherlands Tel. (+31) 30 - 244 05 50
Higherway	yes	Tad Winiecki	Higherway Transit Research

[1] 2getthere is a new subsidiary of Frog Navigation Systems, but in this report we continue to use the name Frog since the change was made while the report was in development.

System Name	Partic-ipated in study?	Contact Person, email, web address	Postal address, Phone (USA unless otherwise noted)
		winiecki@pacifier.com http://www.artwerkz.com/h/	16810 NE 40th Avenue Vancouver, WA 98686-1808 Tel: 360 574-8724
MAIT	yes	John Greenwood john.greenwood@argonet.co.uk http://www.maitint.org	MAIT international e.V. Laenggassstr. 54 CH-3012 Bern Switzerland
MegaRail	yes	Kirston Henderson kirston.henderson@megarail.com http://www.megarail.com	MegaRail PO Box 121728 Fort Worth, TX 76121 Tel: 817-738-9507
MicroRail	yes	(same company as MegaRail)	
Mitchell	yes	Peter Mitchell pitchell@aol.com no web site	Mitchell Transit Systems, Inc. PO Box 343 Middleburg, VA 20118 Tel: 540-364-1441
Monomobile	no	unknown ard@iac.net http://w3.iac.net/~ard/	
Pathfinder	yes	Jack Locke JackLocke@cablespeed.com no web site	Pathfinder Systems Inc. 2545-11th Avenue West Seattle, Washington 98119-2504 Tel: 206-285-4041
PRT 2000 (Raytheon)	no	Steve Gluck GluckS@raytheon.com no web site	
PRT Advanced Maglev Systems	no	George Scelzo gscelzoprt@ameritech.net no web site	
RUF	yes	Palle Jensen pallerj@inet.uni2.dk http://www.ruf.dk/	Mogens Balslev A/S and Palle R Jensen Produktionsvej 2 2600 Glostrup Denmark Tel: (+45) 7217 7202
SkyCab	no	Åke Åredal skycab@telia.com http://www.sigtuna.se /main/view.asp?ID=742	
SkyTran	no	Peter Wokwicz peter@wokwicz.com http://www.skytran.net/	
SwedeTrack	yes	Jan-Eric Nowacki nowacki@telia.com http://www.swedetrack.com/	
Synchro-Rail	no	Dr. Haider Al-Abadi abadi@relevet.com http://www.synchrorail.com/	Relevet Limited NW Wing, Bush House London WC2 4PY England Tel: 00 44 (0) 20 7836 3340

System Name	Partic-ipated in study?	Contact Person, email, web address	Postal address, Phone (USA unless otherwise noted)
Taxi 2000	yes	Ed Anderson jeanderson@taxi2000.com http://www.taxi2000.com/	Taxi 2000 Corporation 5164 Rainier Pass NE Fridley, MN 55421 Tel. 763-586-0878
Urbanaut	yes	Einar Svensson svensson@empnet.com no web site	
ULTra	yes	Martin Lowson martin@lowson.f9.co.uk http://www.atsltd.co.uk/	Advanced Transport Systems, Ltd Alpenfels North Road, Leigh Woods Bristol BS8 3PJ England Tel: 44 117 973 7777

Several additional comments were received by the vendors. The comments were compiled with answers and sent to all vendors, to maintain fairness in the information received by each vendor. Some vendors were contacted separately to clarify certain issues as needed.

The study evolved as the information available and the committee's understanding increased. The original 19 questions were not complete, but through subsequent correspondence, we are confident that the major issues are covered and the systems are treated fairly.

The vendors were able to review the draft study and make corrections before final publication.

Little effort was made to double-check the accuracy of the vendor's statements. For example, if a claim was made that a certain amount of money was spent, we simply repeat that information here, and did not contact the funding sources for verification. Some engineering claims may turn out to be unattainable, and we have no way to do engineering studies within the scope of the study to check the claims.

Non-participating vendors

The reason for nonparticipation of some of the vendors contacted is as follows:

- **Cabintaxi** – The Cabintaxi urban transit system was developed by a German joint venture of Mannesmann, and MBB under a program of the German Federal Ministry of Research and Technology. This was a successful $270 million (2002 dollars) development. The development consisted of an elaborate test facility that saw 14 iterations of vehicles with multiple stations. 400,000 vehicle test miles were driven. The original development team left this field at the end of the development program. Cabintaxi Corporation, a US based company, is now active with this technology. Their business model calls for private sector, building-owning-operating of systems through the sale of service, and hence did not wish to participate in this comparison study.
- **CULOR** – Conceptual only.
- **Flexitrain** – Not true PRT.
- **Monomobile** – Contact not successful.
- **PRT 2000** (Raytheon) – Company reports "There is no new information about Raytheon's PRT. We are no longer pursuing new business for the system, but expect that one of the companies with whom we are in contact will be carrying forward what we and the RTA initiated."
- **PRT Advanced Maglev** – Company reports: "Because of our special commitment in the PRT field, we will not be submitting any information concerning our systems."
- **SkyCab** – Contact not successful.
- **SkyTran** – Venture capital sources require that the details of this system not be made public (however, there is some information on the web site).
- **Synchro-Rail** – Contact not successful.

Study organization

Instead of taking the approach of listing all information for system A, then all information for system B, etc., the information is conceptually grouped. In certain groups (e.g. capacity, noise) the findings are expected to be similar for many systems, so this allows the information to be presented once, instead of repeatedly for each system.

The sub-sections are as follows:

Basic description, appearance, size, geometry
Development status
Guideway Structure
Vehicle, passenger comfort
Propulsion system, grade, traction
Switching and steering
Control, reliability, capacity, related information
Environmental, energy
Safety
Operational characteristics
Flexibility, risk
Cost and value
Characteristics of a specific installation

Where the heading "Evaluation Criteria" occurs, this indicates the list of requirements that a potential customer would probably have, in the committee's estimation.

Sources

Some of the organizational concepts and evaluation criteria were derived from the 1978 book by Jack Irving, *Fundamentals of Personal Rapid Transit,* hereinafter referred to as *"Fundamentals"*. The book is available on the ATRA web site (www.advancedtransit.org), or will be available soon.

Fundamentals includes a thorough discussion of the concepts and detailed calculations of the specialized engineering topics. If a potential customer wanted a third-party technical review of a system, this book would be a starting point for the review engineers. The current study does not include that detailed level of review.

Fundamentals includes information about topics that we have left out because they do not distinguish one system from another. Concepts about the basic definition of PRT (off-line stations, on-demand service, etc.), station design, and network layout, for example, are concepts that apply more or less equally to all systems, and do not distinguish one system from another. Such concepts are therefore left out of the current study.

We would like to thank Lawrence Fabian of Trans21 for providing us with a free copy of the report, "Planner's Guide to Automated People Movers – 2000". To obtain the new 2002 edition of the guide, Mr. Fabian can be reached at:

Trans21
PO Box 249
Fields Corner Station
Boston, MA 02122
617-825-2318
lfabian@compuserve.com

Definition of PRT and GRT

PRT is defined by ATRA as follows:

1. Fully automated vehicles (i.e., without human drivers).
2. Vehicles captive to the guideway, which is reserved for the vehicles.
3. Small vehicles available for exclusive use by an individual or a small group traveling together by choice. These vehicles can be available for service 24 hours a day, if desired.
4. Small guideways that can be located aboveground, at or near levelground, or underground.
5. Vehicles able to use all guideways and stations on a fully connected (a "coupled") PRT network.
6. Direct origin to destination service, without a necessity to transfer or stop at intervening stations (i.e., "non-stop" service).
7. Service available on demand rather than on fixed schedules.

Differences and rationale

There are differences between Group Rapid Transit (GRT) and Personal Rapid Transit (PRT).

The similarities are numerous, which may cause some planners to blur the distinction. The technologies are quite similar, in terms of the guideway, vehicles, and control system. In fact, the exact same system could conceivably be used as PRT or GRT with only software changes.

The true distinction between the two is the service offered.

- PRT service is offered to an individual or group wishing to travel together, and therefore the vehicle goes non-stop to their destination. The existing technology that compares with this service mode is the taxi. While people sometimes share taxi rides, that occurs only by their choice, and the same is true with PRT service.
- GRT service, on the other hand, is not private. Many people may board together, and the vehicle stops at each passenger's destination. It skips stops if no one needs to get off or on. A GRT service in a widespread area probably needs to use regional boundaries and hub stations or other methods to group people together who are going to similar destinations. The existing technologies that compares with this service mode are the elevator and the airport shuttle van.

Because of the basic service distinction, several other technology and planning-related differences between PRT and GRT arise:

- GRT vehicles are generally envisioned as larger than PRT vehicles. But, there is no exact line between the number of seats that constitutes a PRT vehicle and one that is GRT. An intermediate size vehicle of 4-8 seats could conceivably offer either type of service.
- A guideway strong enough to carry groups (GRT) is usually larger than a PRT guideway. It may also require smaller spans between supports. Therefore it may be more expensive to build and more intrusive in an urban setting.
- The control software obviously has to behave differently with respect to routing and empty vehicle management.
- Planning of the network layout would be different. A plan for GRT service would more likely follow major corridors only, while PRT service could become a linked network with overall greater coverage.
- Stations may be different. PRT stations need as little as one berth regardless of the overall network size. Typically developers suggest about three berths. GRT stations in predominantly corridor-oriented networks could also have as few as one berth, but stations in widespread networks (particularly hub stations) would need many berths in order to group people together by their destination region.

Having said all this, what then is the argument for GRT? One argument is that there is a cost savings in vehicles and energy to use fewer, larger vehicles, rather than many small vehicles. This could be true if the network is very simple or is just a single corridor or loop, or transfers are sometimes necessary as with traditional mass transit. PRT advocates counter this argument by reasoning that larger vehicles force the guideway and stations to be larger, and this cost increase is more than GRT's cost savings in energy.

Another argument for GRT is that it appears more acceptable or plausible to the public because it is like mass transit, and therefore doesn't require as big of a paradigm shift. The line of reasoning is that GRT service could be offered first, then it could change to PRT service as the network expanded, or PRT service could be added. If GRT turns out to be more marketable than PRT, its development and deployment would certainly help the technical development of PRT.

A GRT system in operation

One GRT system is currently operating in Morgantown, WV, USA. Built 30 years ago, the Morgantown system is often inaccurately referred to as "PRT" but it is really GRT according to the definitions here. This system demonstrates some aspects of PRT, such as automated control and switching. It also has a good safety record, and has sometimes been the only operating transit system during snowstorms.

However, it does not demonstrate the service aspects of PRT. The layout of the system is a single corridor, with no spurs or loops. Therefore it behaves very like mass transit. The only service distinction is that it sometimes skips stops. A small mass transit system could also work in that corridor. For these reasons, one should not look to the Morgantown system as an example of what PRT (or even GRT) could do.

Comparison of GRT and PRT systems

Austrans, Cybertran, Ruf, and Urbanaut are marketed as GRT and/or dual-mode systems. Noting the similarities of the technology, the committee made the assumption that these vendors could and would sell a PRT system. They are developing GRT because they believe this approach will more likely result in a sale, but if a buyer is ready to buy PRT, they should be able to make the software revisions necessary to support PRT service.

For the purposes of this report, therefore, we include all these systems, but only on the assumption that they are operating in PRT mode. We assume that the larger 6-20 passenger vehicles of these particular systems would pick up only one passenger (or a group wishing to travel together) and make a non-stop trip to his or her destination. It may seem irrational that such a large number of seats would be empty most of the time; however, that is how we are conducting this comparison.

We are aware that systems offering vehicles seating six or more passengers *may* be more expensive to build than the smaller systems, but do not want to make that assumption, because there are many other factors that go into cost besides vehicle size.

In this report we are only comparing and making recommendations about PRT systems, and advocating PRT generally. We are not advocating for GRT systems, nor arguing against them, nor making any recommendations about GRT service.

Please keep in mind the differences between the two kinds of serve, and the limitations of this report, when reading literature from the developers of the systems marketed as GRT. We not are not necessarily promoting the same use of their technology as they are.

Basic description, geometry, and developmental status

Please note that the information in this section is intended mainly to compare the size and configuration of the different systems. More drawings and pictures are available on most of the vendors' web sites.

Skyprint

In order to make a comparison of the visual obstruction of the various systems, we invented a term and measure for the purpose. A "skyprint" of an elevated guideway is the amount of the sky it blocks when viewed from a 45 degree angle from beneath. In order to make the comparison independent of the viewing distance, it is not stated in degrees, but rather distance (in meters).

Visual obstruction in the vertical dimension has the disadvantage of blocking views of landscapes, and obstruction in the horizontal dimension has the disadvantage of creating a roof effect over streets. All systems have some obstruction in both dimensions, of course, but some are more vertical (such as MicroRail) and some are more horizontal (such as ULTra). The choice of 45 degrees was made as a simple compromise to combine both kinds of visual obstruction measures in the same measurement tool.

Evaluation criteria

- System can achieve the value of PRT service by having exclusive rights of way, and dense station spacing at roughly 1 km intervals.
- Guideways can be located aboveground, at or near ground level, or underground.
- Curves can be tight enough to fit into urban intersections; this implies a maximum of about 20 m.
- Vehicles are able to use all guideways and stations on a fully connected (a "coupled") PRT network.
- System fits into urban form aesthetically (subjective).

- Guideway skyprint (see above) is small. (See note.[2]) Smaller skyprints are more desirable: 2 m is good, and 1 m or less is excellent.
- Guideway supports should cause minimal disruption at street level – this implies minimum pier diameter or cross section (0.5 to 1.0 m)
- System is flexible enough to allow it to be aligned mostly within existing street rights-of-way, and to be able to weave through obstructions such as roadway overpasses.
- Stations can be building integrated.
- When aboveground, can span a 6-lane arterial road without intermediate supports.

Categorization of the systems

The systems can be conceptually grouped as follows to aid the reader. The order of presentation of the systems in this subsection will be based on this scheme, rather than alphabetically.

Supported, simple PRT:

Austrans
Autran – also provides ferries for conventional cars
Cybertran
Megarail/Microrail – also provides ferries for conventional cars
Mitchell
Taxi 2000
ULTra – also provides pallets
Urbanaut

Suspended, simple PRT:

Higherway – PRT and dual mode
Pathfinder
SwedeTrack – also provides pallets

Other:

Frog / 2getthere – drives on roads
MAIT – concept for handling transport modules across multiple carriers
Ruf – dual-mode

Autran, MegaRail, and MAIT are generalized systems for carrying anything, and their usage for PRT is a subsystem of the generalized system.

The principal tradeoff in geometry is the type of interface between vehicle and guideway, including the orientation (suspended or supported) and the location of the wheels' running surface. This choice is fundamental, and affects most other aspects of the systems.

[2] This benefit may be relaxed when accounting for the number of passengers served. A specific PRT line that benefits the same size population as does a 4-lane highway, for example, should be judged against the highway in terms of visual appearance and obstruction.

Common points of all systems

All systems meet the basic definition of off line stations, close station spacing, and on-demand small-vehicle service. These characteristics will therefore not be repeated for each system.

Additionally, all *supported* systems (vehicle on top) share these features:

- Vertical piers are spaced at some nominal interval, which is varied for local conditions. Like any bridge structure, beams can be made stronger for larger spans. In cross section, the vehicles ride directly over the piers, (see drawings) so the width of the right-of-way is smaller than for suspended systems.
- When at-grade construction is called for, there is no more visual obstruction than for a one-lane road.

All *suspended* systems (vehicle underneath) share these features:

- Vertical piers are spaced at some nominal interval, which is varied for local conditions. Like any bridge structure, beams can be made stronger for larger spans. The piers extend higher than the vehicle roof, and are cantilevered. The guideway hangs from the cantilever. In cross section, the vehicle travels next to the support piers, and the airspace directly under the vehicle is unobstructed.
- For two-way guideways, the cantilever can be modified by building two poles and a truss between, or an arch shaped structure that vehicles pass under. Higherway specifies this type of construction.
- Guideway traction surfaces are completely shielded from the weather, since the only opening is on the bottom. Supported systems generally have some weather penetration even if they use covered running surfaces.

Summary evaluation of development status

This table is a snapshot of the development status of each system – details follow below.

System	Funding to date (2001 M$US)	Development approach	Status
Austrans	5.3	established engineering firm	prototype built, engineering in progress and substantial parts completed
Autran	1.0	private inventor	preliminary design
Cybertran	5.0	US national lab	prototypes built, not final but substantial parts completed
Frog	confidential	small company	prototypes built, engineering in progress and substantial parts completed
Higherway	0.1	private inventor	preliminary design
MAIT	0.1	private inventor	simulation software written
MegaRail & MicroRail	1.0	small company	engineering in progress with limited prototype
Mitchell	2-4	private inventors	prototypes built, proof of concept and detailed engineering
Pathfinder	2.0	small company	preliminary design

System	Funding to date (2001 M$US)	Development approach	Status
Ruf	1.5	university/small company	engineering in progress; a short test track is operating with a maxi-ruf full scale mock-up
SwedeTrack	?	small company	preliminary design
Taxi 2000	32.6	university/small company	paper engineering including control system highly developed, but no prototype built yet
ULTra	<10.0	university/small company	prototype built, engineering in progress and substantial parts completed and tested, funding in place for passenger service
Urbanaut	"several"	private inventor	early engineering with mini-model built

Explanation of the drawings

On the following pages, each system is shown in various block diagrams to show its size relative to other systems. The shapes are not representative of the actual vehicle shapes. Their only purpose is to show relative sizes of the systems. The reason for showing and comparing these sizes is because the visual impact of PRT is often perceived as a major argument against its implementation.

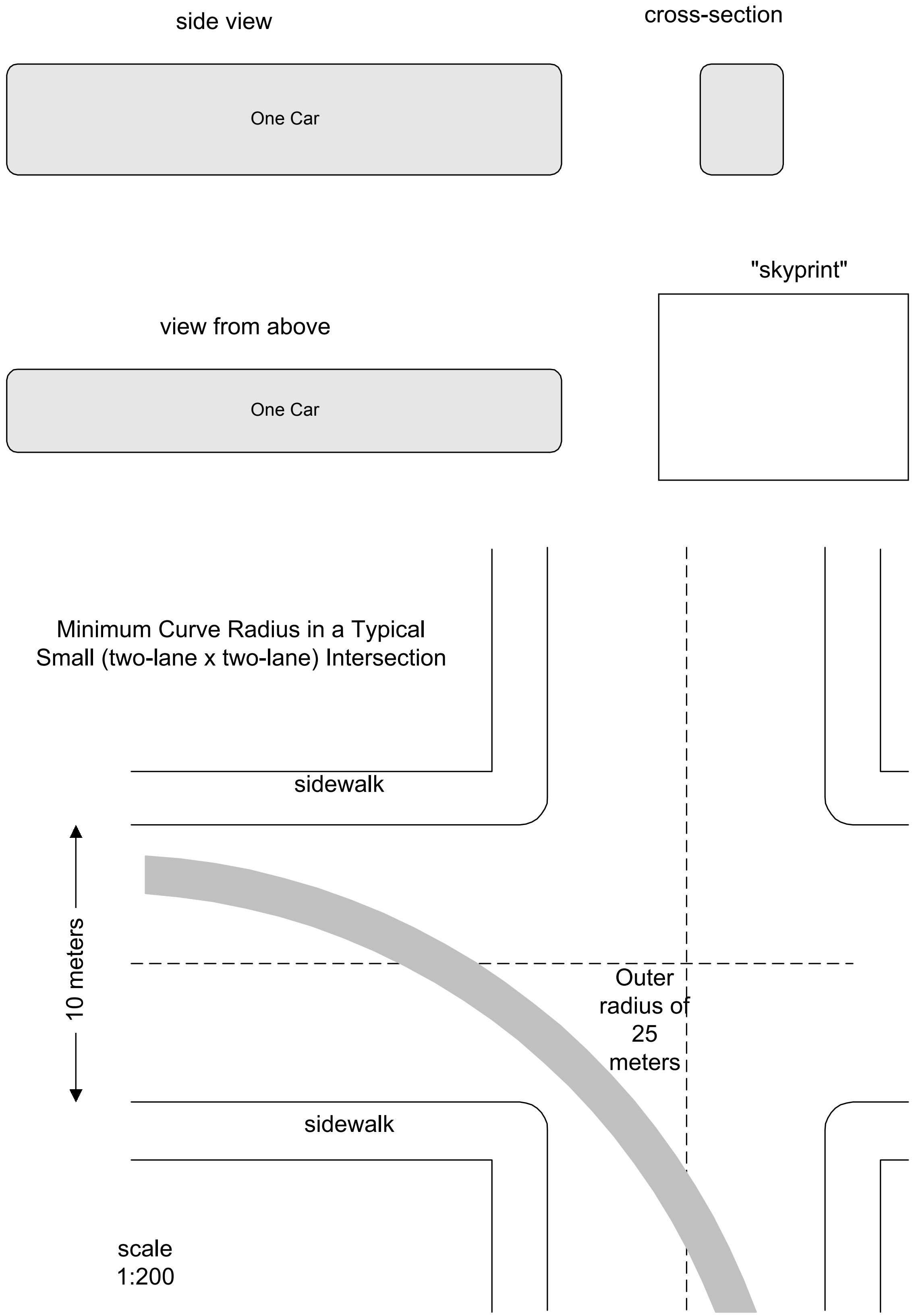
- The side view shows the guideway and vehicle from the side with piers. The piers are shown the same size for all systems, and the dimensions should not be taken literally. Notice that in some diagrams, the vehicle is below (suspended) from the guideway and sometimes above (supported). In some cases the vehicle height overlaps with the guideway height, and in other cases it is vertically separate. (We know of no reason why this difference would affect the aesthetic quality of any system.)
- The cross section shows the size of the vehicle and guideway cross-section, that is, looking at the nose or tail of the vehicle.
- The view from above shows the one-way guideway and vehicle from above. Note some vehicles are wider than the guideway; some are narrower.
- The sky-print shows a view which has been invented for the purposes of this report. It is the amount of sky obstructed by the guideway and vehicle when viewed from 45 degrees. In other words, a person standing on the street, looking up at a 45 degree angle to the elevated system would see this span of sky blocked by the system.

Size diagram of light rail

This drawing for light rail is for comparison of size with the subsequent drawings of PRT systems. Rail systems differ in their minimum curve radius, so in this case we chose a median number of 25 m. Note that light rail vehicles overhang the rails somewhat on straight segments and to a much greater degree around curves.

Even in places where elevated light rail would be considered out of the question on the basis of the visual impact, an elevated PRT system, being much smaller, could be considered.

LIGHT RAIL


side view
cross-section
One Car
"skyprint"
view from above
One Car
Minimum Curve Radius in a Typical
Small (two-lane x two-lane) Intersection
sidewalk
10 meters
Outer
radius of
25
meters
sidewalk
scale
1:200

Simple supported systems

Austrans

This vendor DID NOT REVIEW this report prior to publication.

Description

The Austrans guideway is a double steel rail, like conventional rail except it has a different cross section which allows a secondary wheel to grip the underside. The steel wheels are not flanged like conventional rail wheels, and they are angled out instead of parallel. The modifications to conventional rail make it possible to increase traction, reduce noise, and make sharper turns. Switching is functionally similar to conventional rail.

The vehicle seats 9. **WARNING**: Austrans is marketing their system as a GRT system. However, for the purposes of this report, we are making the assumption that it could operate in PRT mode, in which case the 9-passenger vehicle would pick up only one passenger (or a group wishing to travel together) and make a non-stop trip to his or her destination. Please keep this distinction in mind if you compare the results of this report with Austrans literature. Austrans is built for higher speed than would be necessary for urban PRT.

Dimensions (m)	Height	Width	Length
Vehicle	2.25	1.9	5.4
Guideway	1.05	1.1	
Min. curve radius		8	
Skyprint	1.5		

Status

Quoting the company, "The Austrans engineering team includes professional mechanical engineers, control engineers, industrial designers, automotive engineers, electrical engineers, electronics engineers, mechatronics engineers, etc. In addition the team has access to acoustics and transportation consultants, etc. Company staff are very familiar with production machinery and tooling for manufacture. There are a number of companies such as composite manufacturers and steel makers that are liased closely with Austrans."

AE Bishop, the parent company, is an established Australian engineering firm with other products.

Au$10 million has been invested in Austrans R&D over an 11 year period. ($5.3 M US) with the bulk of that being spent since 1995.

The state of development is:

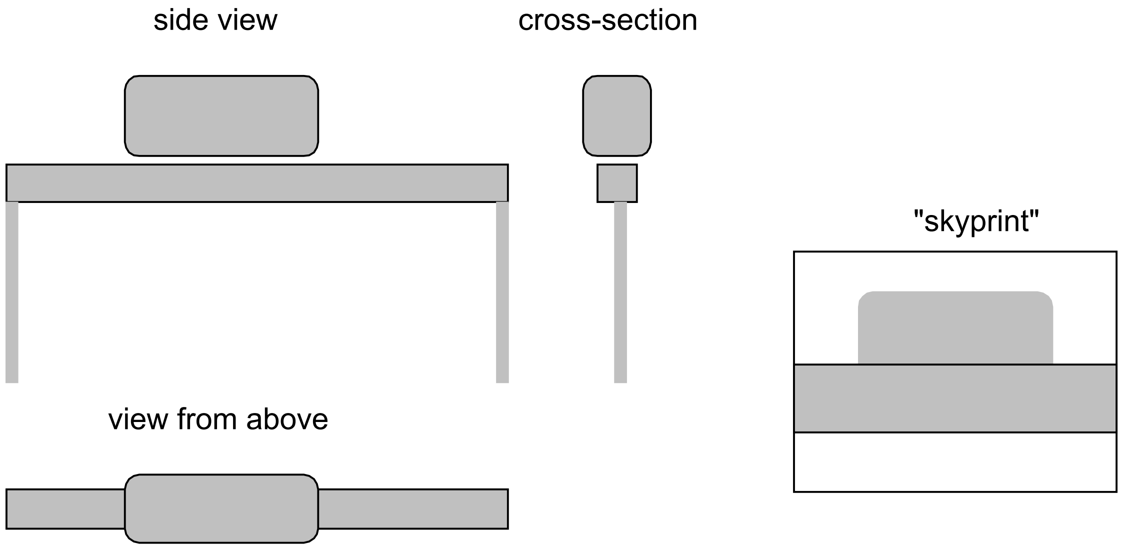
- first test track at Chullora, Sydney built and operational
- first prototype vehicle produced and currently undergoing development trials
- vehicle negotiates 8 meter radius curve as designed, brakes and accelerates as expected - about to proceed with testing ride characteristics when negotiating chicanes
- prototype switch constructed and undergoing development - operates in less than one second. Notable for lack of noise.
- station concept and specification completed
- proprietary simulation software developed

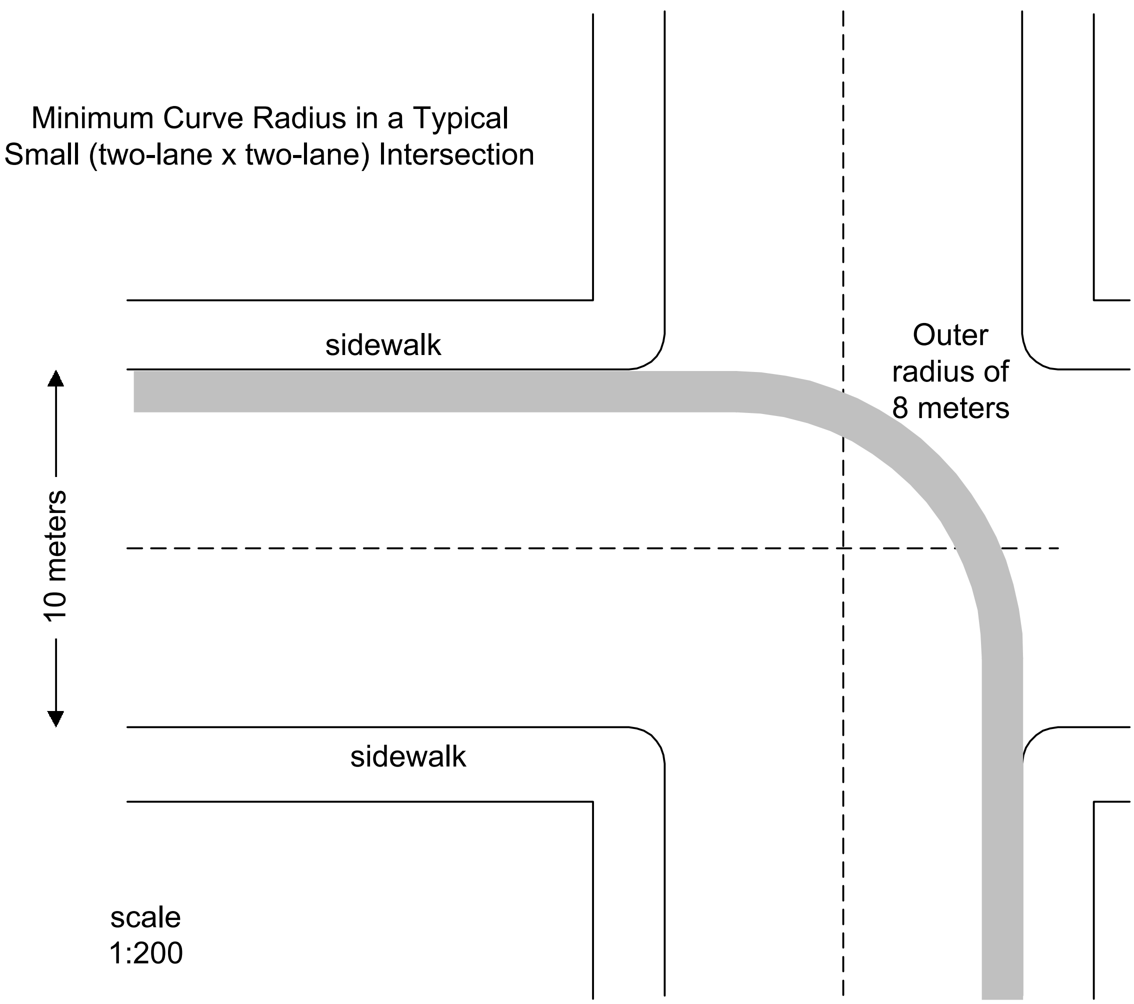
Evaluation

The system fell short on these evaluation points: (1) Rail surfaces are exposed to the weather and so the system may have reduced traction when ice is present. This would influence the safe following distance (which impacts capacity), and could limit grade-climbing ability. (2) Vehicle separations were not reported.

Summary: Austrans appears to be undergoing a rigorous development process, which is not yet complete. We have no reservations about its ability to perform as advertised, with the information we have available.

AUSTRANS


side view
cross-section
"skyprint"
view from above


Minimum Curve Radius in a Typical
Small (two-lane x two-lane) Intersection
sidewalk
Outer
radius of
8 meters
10 meters
sidewalk
scale
1:200

Autran

This vendor REVIEWED this report prior to publication.

Description

Autran is a supported technology that resembles the simple supported systems, but also has pallet carriers for cars. The company envisions wide scale networks carrying freight containers, pallets and dual-mode cars as well as PRT/GRT cabins. They assert that PRT advocates and dual-mode advocates can help each other by using a system designed flexibly from the start for both purposes.

The PRT vehicle seats 4. The GRT vehicle seats 8.

The guideway is a single box beam with a slot at the top. The wheel set is entirely inside the box beam. Two sizes are planned: a lightweight size for PRT and light freight, and a heavier size for auto-carrying pallets. The small 2-4 passenger PRT vehicles will be able to use both guideway types.

The guideway is constructed in spans of 20 m using two prestressed concrete side beams that support steel frame members for support of tracks. Adjustments of the positions of frame members relative to the beams can be made to obtain very smooth travel.

Steel wheels on steerable front and rear bogies are driven by an induction motor through an electronically controlled transmission and two differentials. Steering, switching and increased traction when necessary are all obtained through control wheels engaged with separate tracks. The vehicle can negotiate tight radius curves because the front and rear axles swivel on a vertical axis.

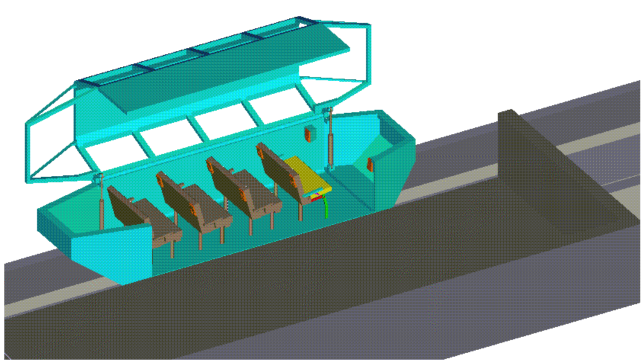
The current design is for supported vehicles/carriers, but features of the design could allow for suspending vehicles in the future.

The system includes a tilting mechanism which improves comfort in curves. Loads are automatically tilted as a function of speed and the radius of a curve.

Dimensions (m)	**Height**	**Width**	**Length**
Carrier vehicle [3] (inside guideway)	0.8	1.3	2.75 (wheelbase)
PRT Vehicle	1.6	1.1	3.3
GRT Vehicle	1.6	1.1	4.75
Guideway	1.4	1.8 [4]	15 m sections
Min. curve radius		5.2	
Skyprint	2.3		

Status

The principal engineer and president of Autran, Van Metre Lund, has a 1944 B.S. degree in Electrical Engineering from Iowa State University. He is solely responsible for all engineering but has had assistance and encouragement from many people, particularly including professors at the Illinois Institute of Technology and people at the Transportation Center of Northwestern University. Mr. Lund retired over 10 years ago, after a career of over 40 years in obtaining patents for others on a wide variety of electronic and mechanical inventions. He has since been working full time in engineering and obtaining U.S. and foreign patents on the system. To date, seven U.S. patents have



[3] The dimensions of the bogie or wheel set are not normally given. Autran refers to the in-guideway wheel set as the "vehicle" (not a bogie) and it is designed to carry various loads, so its dimensions are given.
[4] Width increased in turns.

been issued.

Expenses have not been determined but have been at least $50,000. The investment of time could be valued at over $1,000,000 if measured at rates that could have been charged to others.

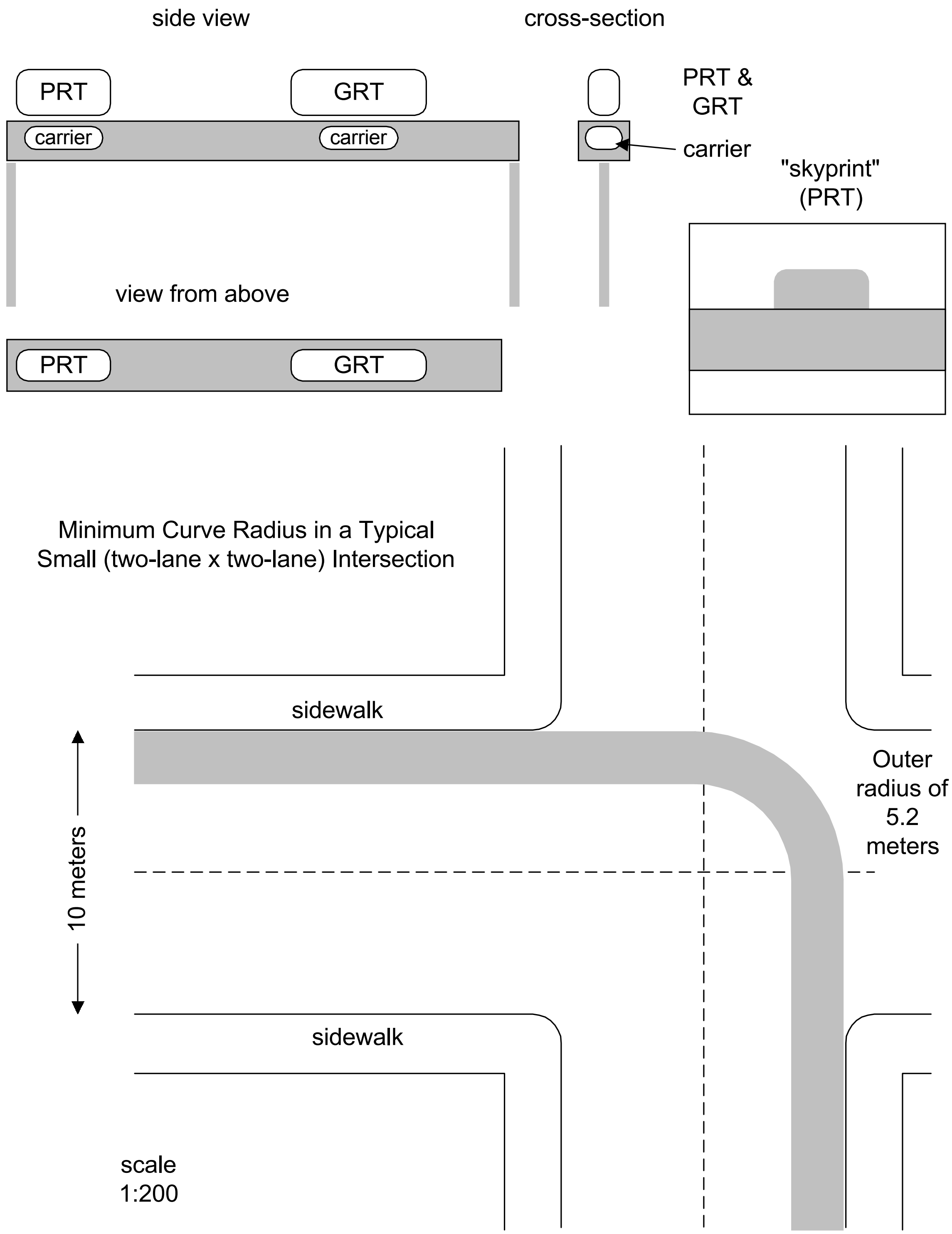
Detailed engineering drawings have been made on carrier vehicles and guideways of the system, also for stations that load cars on pallets and for dual-mode cars. No full scale prototype has been made, but models have been made to test critical aspects of the designs of vehicles.

<u>Evaluation</u>

The system fell short on these evaluation points: (1) The skyprint is “marginal”. (2) There is only one motor in the vehicle.

Summary: Autran is in the preliminary engineering stage.

AUTRAN



side view
cross-section
PRT
GRT
carrier
carrier
PRT &
GRT
carrier
"skyprint"
(PRT)
view from above
PRT
GRT
Minimum Curve Radius in a Typical
Small (two-lane x two-lane) Intersection
sidewalk
Outer
radius of
5.2
meters
10 meters
sidewalk
scale
1:200

Cybertran

This vendor REVIEWED this report prior to publication.

Description

The Cybertran guideway is a double steel rail, like conventional rail, with the standard gauge of 56.5 inches. Single axle propulsion bogies allow for tight turns with low wheel/rail wear and low noise.

Six of the standard steel guideway sections are field welded together to provide an operational unit 97 m long, at the end of which temperature expansions are handled, emergency egress to the ground is provided, and sensor packages of system control are located.

A second type of guideway section is a pre-stressed concrete section with the same dimensions as the steel section, but not rigidly connected in the field. This guideway type is approximately 10 times heavier than the steel version and is used where aesthetics rule out simple steel sections.

The vehicle types have different seating arrangements, but only one body size is proposed. Seating ranges from 6 to 20. Multiple doors provide direct access to each seat or row of seats, with easy ADA accessibility. Propulsion units are designed to utilize a variety of motors and power transmission units, depending on speed range and power requirements of application. The long 11+ m length is partly due to aerodynamic cones on both ends.

WARNING: Cybertran is marketing their system as a GRT system. However, for the purposes of this report, we are making the assumption that it could operate in PRT mode, in which case the vehicle would pick up only one passenger (or a group wishing to travel together) and make a non-stop trip to his or her destination. Please keep this distinction in mind if you compare the results of this report with Cybertran literature. Cybertran is built for higher speeds than would be necessary for urban PRT.

Dimensions (m)	Height	Width	Length
Vehicle	1.9	1.9	11.6
Guideway	1.6	2.6	16 m sections
Min. curve radius		16	
Skyprint	3.0		

Status

The CyberTran team is led by the developer of the system, Dr. John A. Dearien. Dr. Dearien is a Professional Engineer with degrees in Civil and Structural Engineering and 30 years experience with the Idaho National Engineering and Environmental Laboratory. He has served in a variety of technical and management positions ranging from the development of computer codes for nuclear reactor safety evaluation to development of power plants for Star Wars weapon platforms to nuclear rocket system for travel to Mars. Dr. Dearien developed the CyberTran system as part of a systems engineering project to improve the transportation infrastructure of the INEEL. Dr. Dearien's background and experience in the Civil, Structural, Mechanical, Power, and Computer sciences allows him to cover most of the important and costly aspects of transportation systems.

The CyberTran development team consists of 15 people at present in a range of employment with full time, part time, and on-call-as-needed personnel for tests and special development activities. The capabilities of this team include systems engineering, planning with the NY Subway system, pertinent aspects of civil, structural and mechanical systems, electric power transmission and application, computer control and sensor development, radio transmission and control, and rail dynamics, as well as legal and financial control expertise. In addition to the individual capabilities, working relationships have been established with a vehicle design company, two steel fabrication companies, an industrial architectural firm, and 2 major A&E firms (one US and one British) with extensive experience in the design and construction of rail transit systems.

Approximately $5,000,000 has been spent to date in developing and testing CyberTran. This sum includes grants and funding from the U.S. Department of Energy and the U. S. Department of Transportation, funding from private companies, equity funding from investors, personal funds expended by system developers, in-kind labor, *pro bono* evaluations, and donations of material and hardware.

Development and testing have been in progress for 12 years to date.

The first CyberTran test vehicle was built and tested at the Idaho National Engineering and Environmental Laboratory (INEEL, a U. S. Department of Energy R & D laboratory) in a year long program from September 1989 to September 1990. Testing and evaluation of the concept continued at the INEEL over the next 8 years with tests on self steering, automated control, vehicle manufacturing techniques, development of a second test vehicle, and evaluation of various guideway designs, passenger handling issues, and safety systems.

The technology was moved to the former Alameda Naval Air Station in Alameda, California in 1998 where testing continued to demonstrate the guideway switch and grade climbing ability of the vehicle. Testing continues to date with emphasis on the automated control system.

Two test vehicles have been built and tested for a variety of operational parameters. Test tracks have been built in Idaho and California for specific tests and a new test track is being planned. Five different test series have been performed with the two test vehicles demonstrating

(1) basic vehicle and track behavior,
(2) self steering of single axle propulsion units,
(3) operation of a vehicle actuated switch for rapid track turnouts,
(4) test of motor and power transmission options, and
(5) proof of vehicle grade climbing capability.

The #2 test vehicle is a prototype of the operational vehicle and has been used in the last 3 test series.

A prototype of the elevated guideway has been fabricated and was tested as part of Test Series 5. Design of the prefabricated elevated guideway support column has been verified for use in high seismic zones such as the San Francisco Bay area.

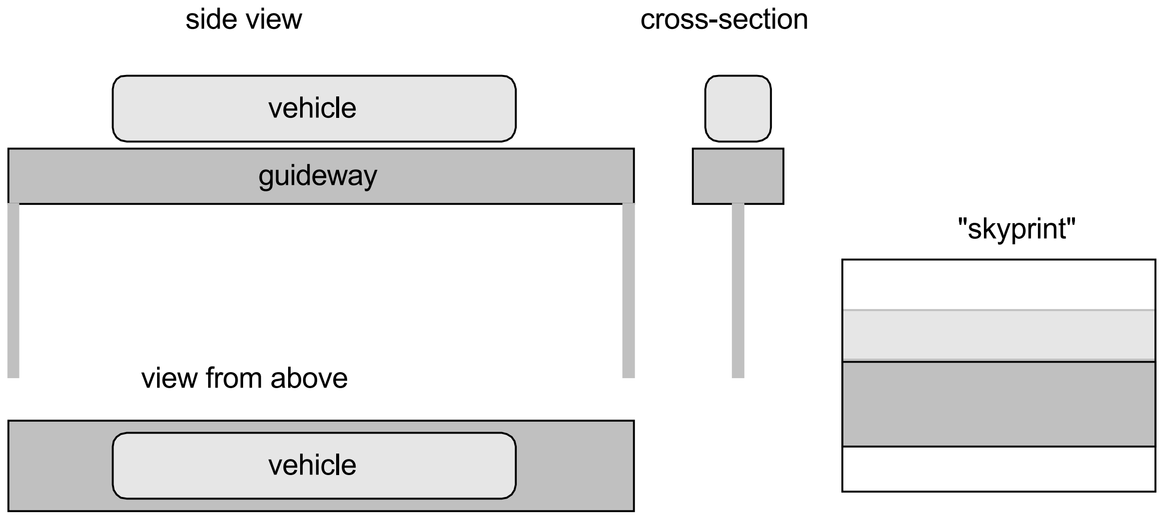
The control system has been defined with computer testing and hardware simulation of the system demonstrated. System operation has been defined and computer simulation of passenger handling has been performed.

<u>Evaluation</u>

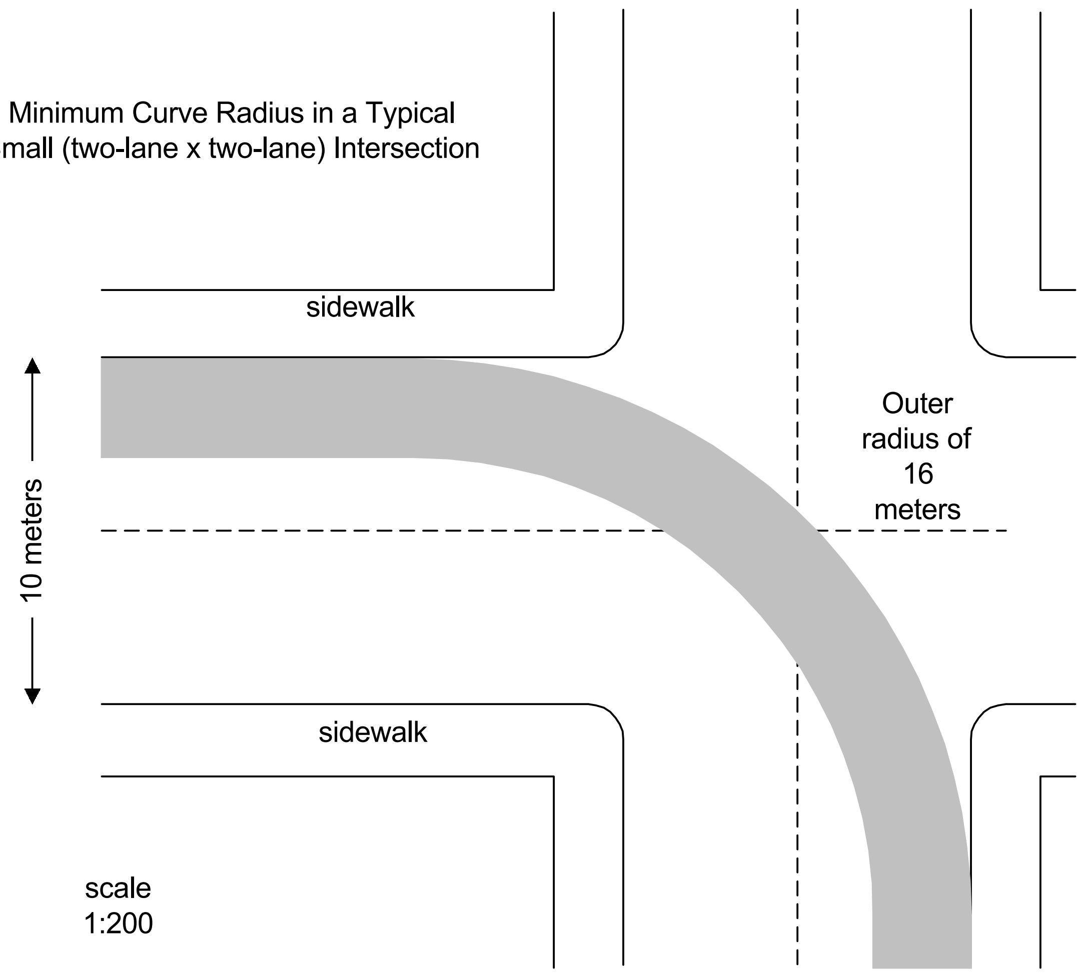
The suitability of Cybertran for use as PRT is restricted due to its long headways of 15 s, and resulting low capacity. Cybertran apparently has a higher speed intercity market niche in mind, which is different than the urban lower-speed niche envisioned by ATRA. Nevertheless, it could be used as PRT. The system fell short on these evaluation points: (1) The skyprint is large. (2) Rail surfaces are exposed to the weather and so the system may have reduced traction when ice is present. This would influence the safe following distance (which impacts capacity), and could limit grade-climbing ability. (3) Vehicle separations are very large, so the system would have very low capacity in PRT service mode.

Summary: Cybertran appears to be undergoing a rigorous development process, which is not yet complete. We have no reservations about its ability to perform as advertised, with the information we have available.

CYBERTRAN



side view
cross-section
vehicle
guideway
"skyprint"
view from above
vehicle



Minimum Curve Radius in a Typical
Small (two-lane x two-lane) Intersection
sidewalk
Outer
radius of
16
meters
10 meters
sidewalk
scale
1:200

MegaRail

This vendor REVIEWED this report prior to publication.

Description

The MegaRail guideway consists of two steel box beams side by side. Wheels are inside the boxes, and the axle passes through slots on the sides of the beams. This configuration provides weather protection for the traction surface, communications, and power pick-up, and it prevents derailment. It also allows for a very small skyprint. The rail beams are self supporting with no superstructure. Wire mesh spans the space between the rails for use as an emergency walkway, but this is designed to block very little light passage.

MegaRail is a multifunction concept, offering pallet transport for cars, plus GRT and PRT service.

The smallest vehicle is a 6-passenger PRT vehicle. The GRT vehicle seats 12. The wheels have rubber tires, with one on each corner of the vehicle.

The system supports more functions than PRT, and offers higher speeds than would be necessary for PRT.

Dimensions (m)	**Height**	**Width**	**Length**
Vehicle	2.2	2.7	6.1
Guideway	0.9	0.33 m per rail, plus 2.24 m open space, totaling 2.9 m	
Min. curve radius		14.7	
Skyprint	0.9 per rail, totaling 1.8		

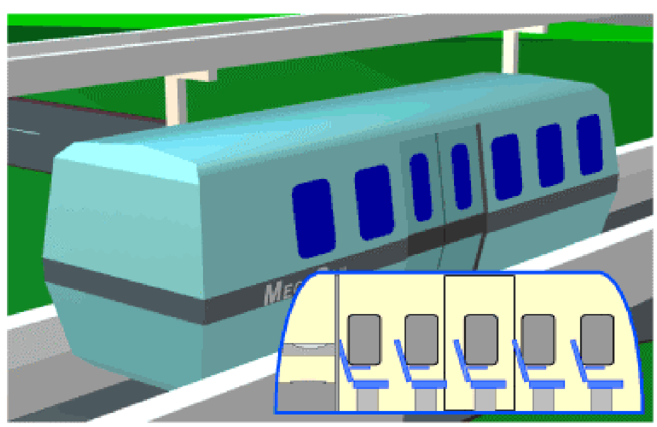
The nominal guideway footprint consists of piers located at 15 m intervals.

Status

Most members of the MegaRail/MicroRail engineering design and manufacturing team have many years of professional experience covering a wide range of electronic systems, mechanical design, complex system software and manufacturing of both mechanical and electronic systems. The team includes registered professional engineers and architects with long and extensive experience. Several of the team members have 40 years or more experience ranging from aircraft systems and communications to automotive systems.

The total value of funding and services committed to development to date has been approximately one million dollars (US). A similar level of additional development funding is planned over the next year. Low level work has been in process for several years, but the development effort was stepped up sharply in mid-2000 following award of a basic U.S. patent covering the system.

A small-scale operating car was built and successfully tested to validate the vehicle steering and switching approach. Detailed engineering drawings for the vehicle, rail and guideway have been prepared. A 1/5-scale prototype is now being built. In addition to the small-scale models, a full-size section of MicroRail guideway has been fabricated, erected, and static load tested.



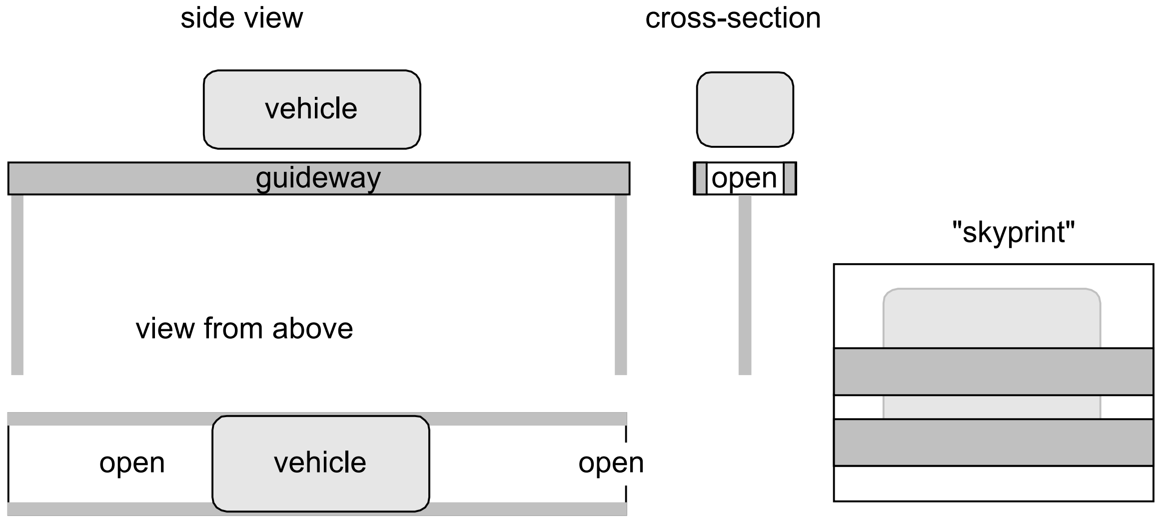
MegaRail and MicroRail are covered by U.S. and Australian patents and several other international and U.S. patents are pending.

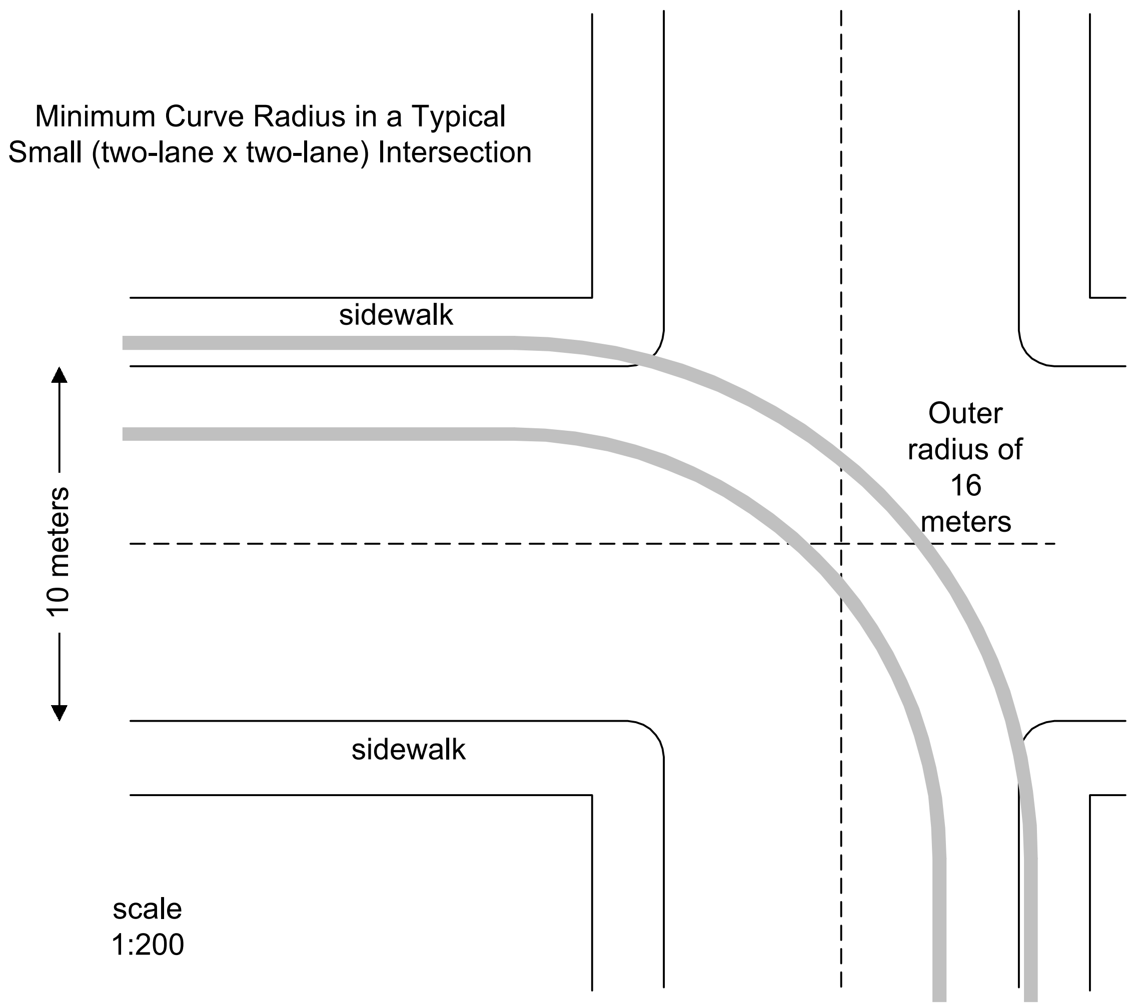
Evaluation

The system fell short on this evaluation point: There are no front windows.

Summary: MegaRail/MicroRail appear to be in a significant engineering effort, but the funding level indicates an early stage of development.

MEGARAIL


side view
cross-section
vehicle
guideway
open
"skyprint"
view from above
open
vehicle
open


Minimum Curve Radius in a Typical
Small (two-lane x two-lane) Intersection
sidewalk
Outer
radius of
16
meters
10 meters
sidewalk
scale
1:200

MicroRail

This vendor REVIEWED this report prior to publication.

Description

MicroRail is the little brother of MegaRail, and is basically the same thing, only smaller. Vehicles seat 4 passengers. The maximum speed is lower (100 kph) and is more in line with the needs of urban PRT service. Pallets are not offered, but dual-mode cars are envisioned.

Dimensions (m)	Height	Width	Length
Vehicle	1.83	1.7	3.1
Guideway	0.7	0.25 m per rail, plus 1.2 m open space, totaling 1.68 m	
Min. curve radius		9.2	
Skyprint	0.7 each, totaling 1.4		

MicroRail guideway and passenger stations will be able to accommodate future electric dual mode automobiles. These cars will be able to drive on the street for short distances at low speeds, and enter and exit MicroRail guideways at special ramps. These cars are under automatic control on the guideway and will use guideway power for propulsion and charging of internal batteries for street use. These cars will also be able to stop at passenger stations for passenger and driver entry and exits and be capable of being stored by the system for later recall by the driver to a passenger station.

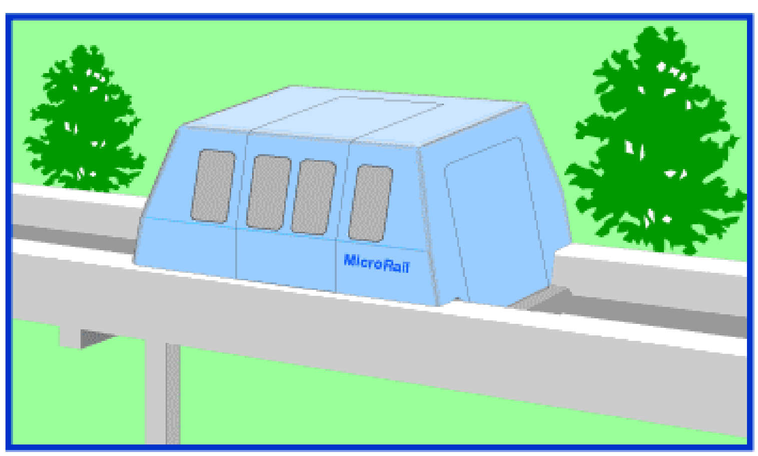
Status

See the status information for MegaRail.

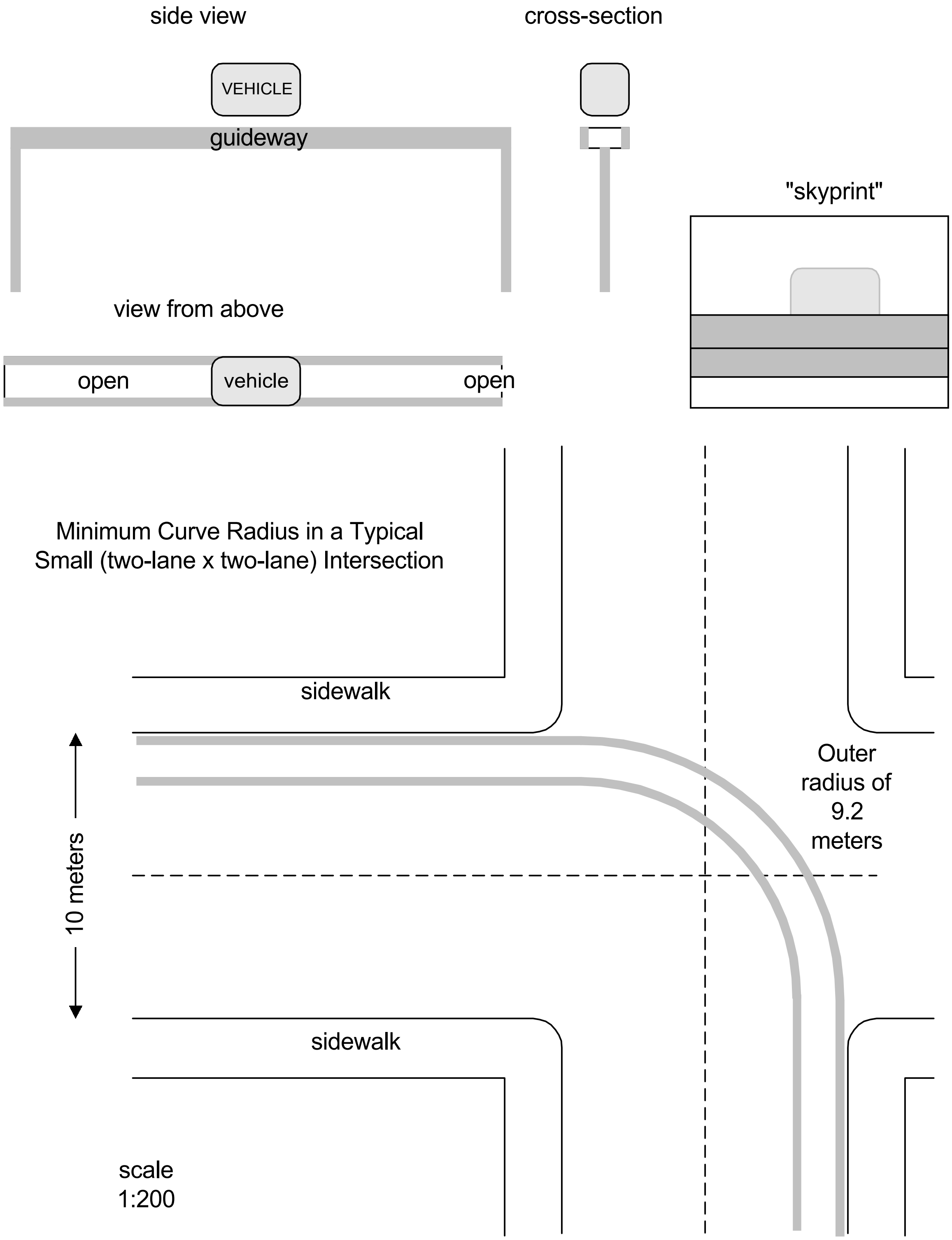
Evaluation

The system fell short on this evaluation point: There are no front windows.

Also see MegaRail above.



Microrail


side view
cross-section
VEHICLE
guideway
"skyprint"
view from above
open
vehicle
open
Minimum Curve Radius in a Typical
Small (two-lane x two-lane) Intersection
sidewalk
Outer
radius of
9.2
meters
10 meters
sidewalk
scale
1:200

Mitchell

This vendor REVIEWED this report prior to publication.

Description

The Mitchell guideway consists of two parallel 0.15 m x 0.15 m steel I-beams spaced at 0.91 m apart, side by side. Each beam is a running surface for the vehicle's wheels. Crossbeams are used to tie the two rails together and transfer load to the piers.

The guideway contains many small motors that physically push the vehicles along. The motors are the basis of the propulsion, braking, and control system.

The lower inside flange of the I-beam rails is the running surface. The upper flange will prevent the lightweight vehicle from escaping the guideway in high wind. The car is always trapped between these rails except at a line intersection where a cover protects it from wind and weather.

The small 1-2 passenger vehicle is primarily a passive shell. Its only active component is the switching mechanism.

Dimensions (m)	Height	Width	Length
Vehicle - std	1.3	1.0	3.9
Guideway - std	0.15	1.0 with gap	
Vehicle – ADA	1.5	1.0	3.9
Guideway – ADA	0.15	1.0 with gap	
Min. curve radius		6 [5]	
Skyprint	0.2 each, [6] total 0.4		

The beams are supported by a steel I-beam post every 7 m (or 19 m for the ADA system). A superstructure to support the guideway allows for flexibility in spanning longer distances or street intersections.

Status

Mr. Brad Willer, PE, is the project manager for MTS (Mitchell Transit Systems). His largest construction project managed was $1 billion.

Rex Mitchell overseas all aspects of manufacturing and fabrication. Mr. Mitchell has extensive manufacturing experience including machine tool building along with his Mitchell Transit design expertise.

Dr. Stan Surrett, MBA, Ph.D., is charged with business and human resource matters. Mr. Surrett has been involved with four high technology start-ups with sales currently $6 billion, including Seimens. Mr. Stan Surrett adds substantial experience in building large organizations out of start-ups. He led the Seimens start-up in

[5] Mitchell's standard minimum radius was reported at 18.2 m, but can negotiate 6 m at very low speed.

[6] This is an estimate and does not take into account the many crossties and motors that would add to the shadow area.

the United States from zero sales to over $300 million in just two years. He has been involved with four start-ups with current sales over $6 billion. Mr. Surrett was materially involved in the sale of LCI to Qwest, a $4.6 billion acquisition.

Mr. Peter Mitchell is the president of the 14-year-old company. He has construction and operational experience and was recently involved with the start-up of the United Airlines $8 million automatic baggage sortation system.

Mr. Bob Dix, Electronics and Communications expert with Shaffer World Communications is the slated supplier of electronics for MTS.

The development of this system was started in 1967 by Bruce Mitchell, an aeronautical engineer working for the Lockheed Corporation, as a Senior Research Specialist, at that time. Lockheed was not interested in developing transit systems then so it was a private undertaking. Initially, it was only a study to see if it were possible to develop a cost effective system that could meet all of the best features desired in public transportation. Three system patents have been obtained on the Mitchell Transit System covering all aspects of the design including the unique propulsion, switching, and control systems and structural configuration.

MTS has built three one passenger sized test tracks. Each track was a 200m loop with one off-line boarding station. The first two tracks suspended the vehicle from the guideway, the latest supported the vehicle. The operational speed was 24 kph.

According to the company, “The principals have invested over $300,000 and 42 man-years in the development of Mitchell Transit Systems.”

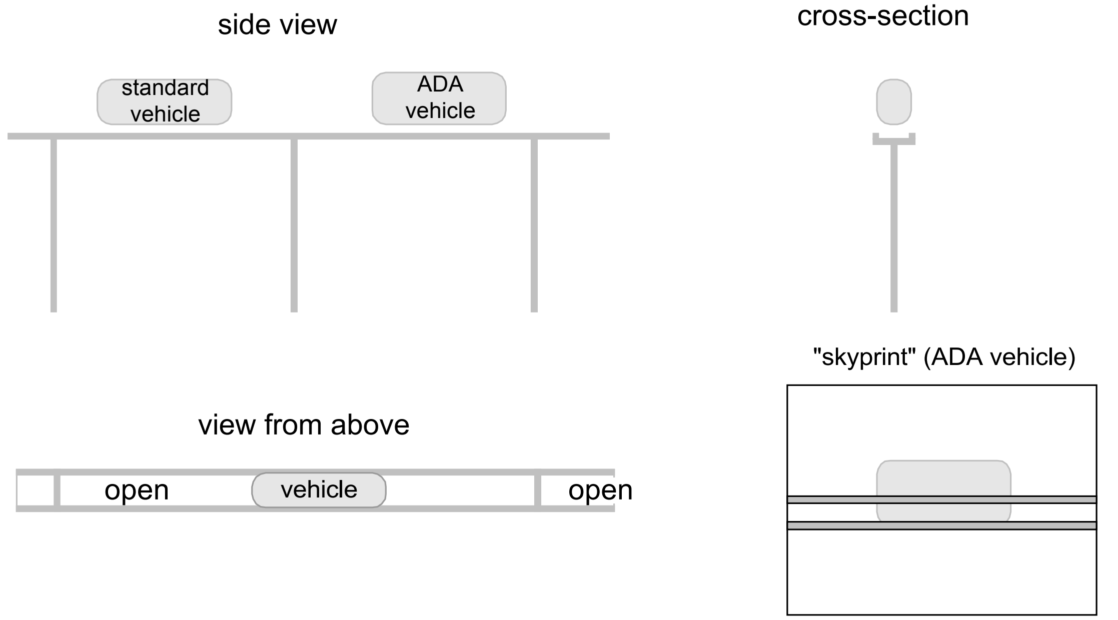
The development of this system has now covered a span of over 20 years with limited and interrupted funding.

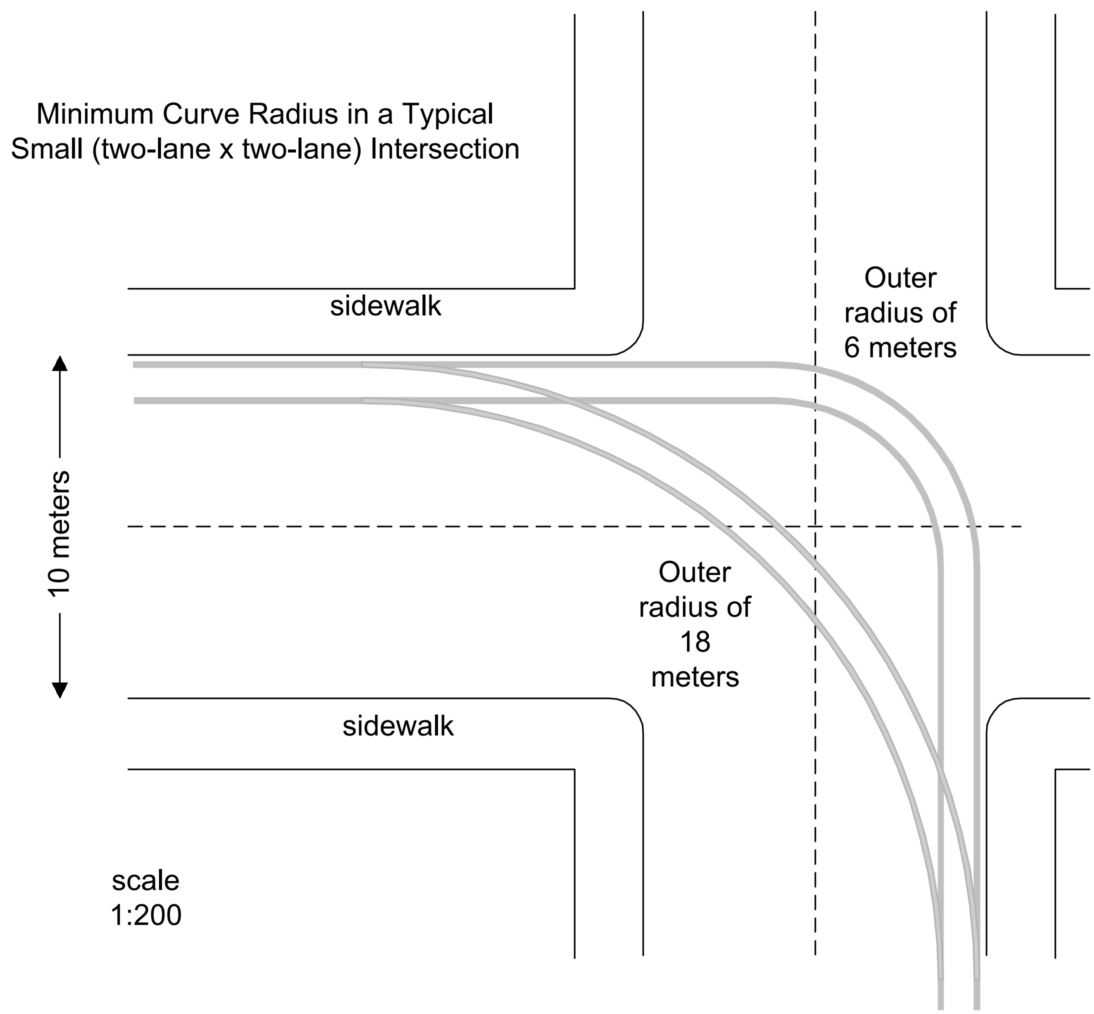
Evaluation

The system passed all evaluation points.

Summary: Mitchell claims its system is 95% complete. We are unable to validate this, although it would prove to be a very low-cost development effort. If 42-man years of labor were included, the development cost would likely be more in line with other systems. We did not understand some aspects of the design.

Mitchell


side view
standard vehicle
ADA vehicle
cross-section
"skyprint" (ADA vehicle)
view from above
open
vehicle
open


Minimum Curve Radius in a Typical Small (two-lane x two-lane) Intersection
sidewalk
Outer radius of 6 meters
10 meters
Outer radius of 18 meters
sidewalk
scale 1:200

Taxi 2000

This vendor REVIEWED this report prior to publication.

Description

Taxi 2000 operates on top of a guideway narrower than the vehicle. The guideway is a single box beam with a slot on the top and bottom. The entire wheel set is inside the beam and the cabin is above the beam. The wheel set consists of a short front axle and a short rear axle, with four main wheels, plus several lateral guidance and switch-related wheels.

The vehicle seats 3.

The vehicle runs on cushion tires and is propelled by dual linear induction motors. It is small and contains a single bench seat facing forwards.

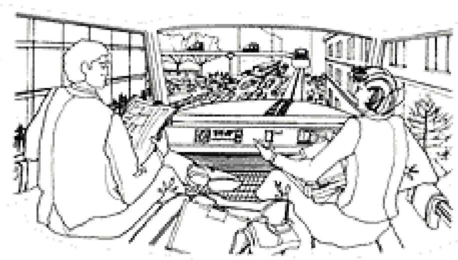
Dimensions (m)	Height	Width	Length
Vehicle	1.52	1.4	2.6
Guideway	1.0	1.0	
Min. curve radius		12 [7]	
Skyprint	1.4		

The vehicle is 1.47 m tall from the interior and station floor to the outside top, and an additional 1 m extending below the floor to the bottom of the main support wheels. The latter measurement overlaps with the guideway height, since the wheels are inside the box beam.

The beams are supported by posts every 29 m.[8]

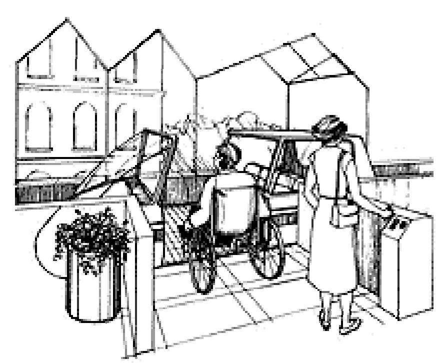
Status

Taxi 2000 was founded by Dr. Ed Anderson, Ph. D. P.E., who is the author of *Transit Systems Theory*, and is perhaps the most widely known long-time advocate for PRT. He has lectured widely and developed courses on transit theory.



The design of Taxi 2000 began in 1982 after 13 years of intensive involvement in PRT including chairing three international conferences on PRT (1971, 1973, 1975), development of the textbook *Transit Systems Theory*, 9 months of Dr. Anderson's work at the Colorado RTD, 18 months at Raytheon in an effort to move that company into the field of PRT, and 3 years as U. S. Representative for Cabintaxi.

Over $32 million in cash and in kind investment has gone into Taxi 2000.



The Taxi 2000 technology was licensed, altered and further funded and developed by Raytheon. This altered system was called PRT 2000. It progressed to a final working demonstration system in full scale before the project was canceled. Raytheon may also wish to sell that system, but declined to participate in this study. Taxi 2000 is a different system from PRT 2000, and Dr. Anderson emphasizes that

[7] There is nothing inherent in the system that would prevent a smaller radius. "Operationally, we have seen no case in which the speed would be low enough so that one could pass through a 36-ft curve radius within ride-comfort limits."

[8] According to the inventor, "I was able to derive an exact solution for a curved beam under uniform load, from which we are very confident about the ability to do 90-ft spans. We meet the AASHTO specification of deflection less than 1/800th of the span with fully loaded vehicles nose-to-tail on the guideway."

Raytheon made design choices that went against the basic principles of Taxi 2000.

Quoting the company, “All the research and development work required has been done. Designs for all subsystems have been developed. Programs have been written to study lateral and pitch motion of the vehicles, from which sizes and placement of wheels and other components have been determined. The guideway in straight and curved sections has been analyzed by computer by Davy McKee Corporation, United Engineers and Constructors, and Stone & Webster Engineering Corporation. Preliminary drawings have been done. What remains is to hire an engineering team to update all specifications and build a test system.”

“None of the components of the system are developmental - all can be procured directly. The software to operate the whole system has been developed, which I believe is unique. Taxi 2000 has won international competitions sponsored by SeaTac, WA (1992), the Chicago RTA (1993), and the Cincinnati Sky Loop Committee (1998) – see www.skyloop.org. No other PRT systems have won any competitions in which we have participated.”

Recently, Taxi 2000 has raised $500k (of $1M sought) for the prototype construction, and component manufacturers have been lined up.

Evaluation

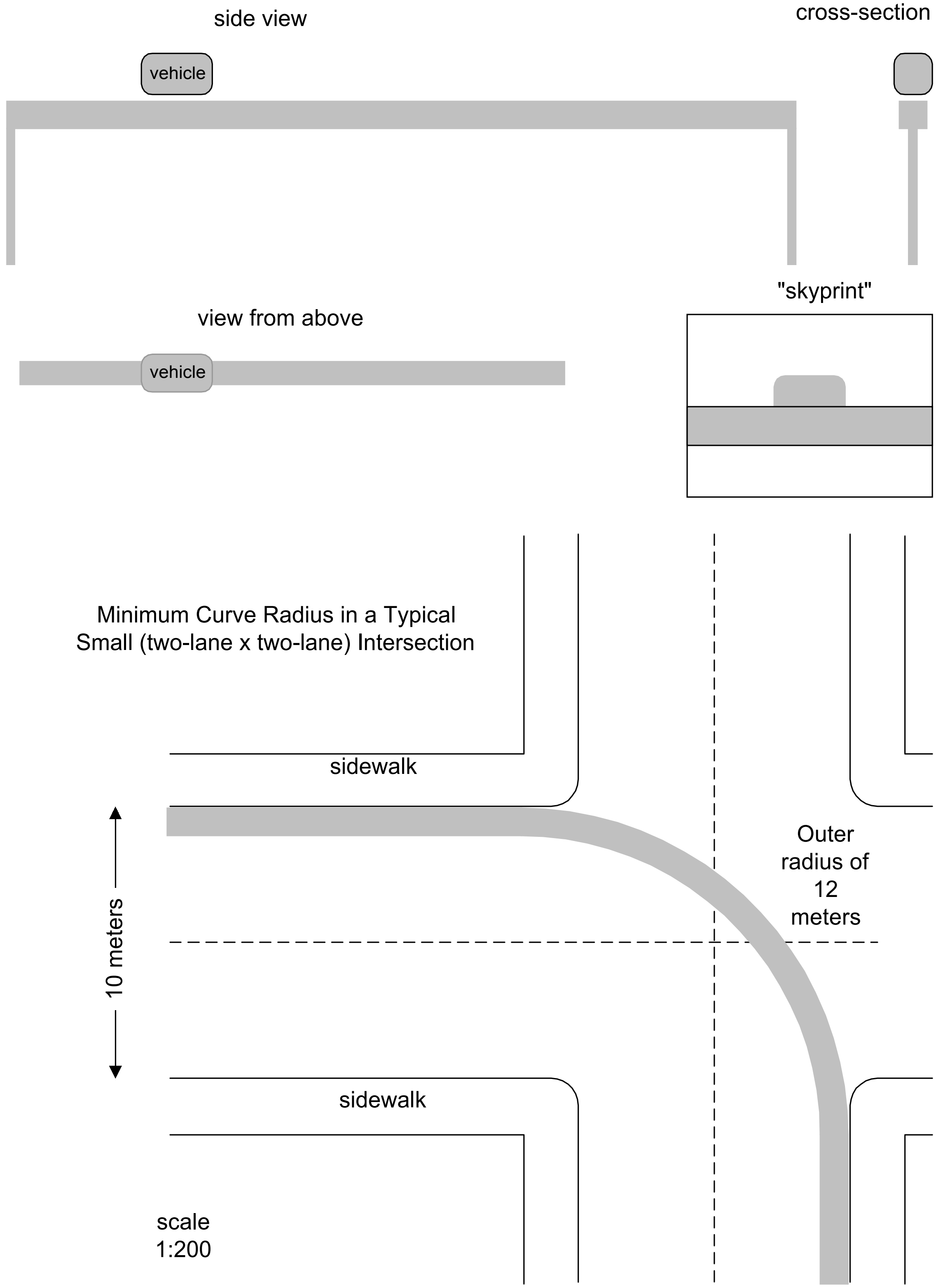
The system passed all evaluation points.

Taxi 2000 is by far the most funded development effort of those listed in this report. (Much more was spent on the development of Cabintaxi, but is not included in the report at their request.). Many of the more specialized issues identified as having been researched and solved by Taxi 2000, such as computer modeling of the vehicle motion, detailed study of forces on each component and required stiffness, etc., were not even mentioned by most other vendors as issues to study, indicating that they may not have gotten that far yet.

Taxi 2000 has not yet built a prototype, but the amount of effort to date (plus the apparent success of the PRT 2000 prototype, which was initially based on Taxi 2000) suggests that a prototype would go smoothly according to design.

Summary: Taxi 2000 has undergone extensive engineering, and still needs to build a test system. We have no reservations about its ability to perform as advertised, with the information we have available.

Taxi 2000



side view
cross-section
vehicle
view from above
"skyprint"
vehicle
Minimum Curve Radius in a Typical
Small (two-lane x two-lane) Intersection
sidewalk
10 meters
Outer
radius of
12
meters
sidewalk
scale
1:200

ULTra

This vendor DID NOT REVIEW this report prior to publication.

Description

ULTra operates on a guideway with a road-type surface and small curbs on each side. The guideway is passive. Power is only supplied in stations or as necessary for recharging vehicle batteries.

The small 4-passenger vehicle is car-like with 4 rubber tires. It is battery powered. The company plans future dual mode cars for the same guideway.

Dimensions (m)	Height	Width	Length
Vehicle	1.7	1.5	3.7
Guideway	0.5	2.1	
Min. curve radius			
Skyprint	1.8		

The nominal guideway footprint consists of piers located at 19 m intervals.

The drawing shows a 6m radius, although none was supplied by the vendor.

Status

The ULTra team is headed by Martin Lowson (CEO), a member of the UK Royal Academy of Engineering and a Fellow of several UK and US Professional Engineering Societies; Chris Cook (COO), previously Main Board Director of British Rail Engineering and responsible for the whole of their new build business (~$1.5B); and Trevor Smallwood (Chairman), previously Chairman of First Group, the UK's largest transport operating company (Turnover $1.5B).

ULTra has been in development since 1995. Total investment now approaches $10M

A prototype vehicle was completed March 2000, under UK Government funding.

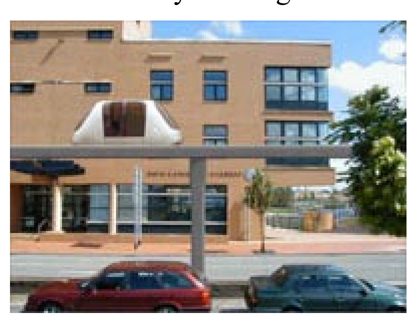
ULTra won the UK Department of Transport innovative transport competition and is consequently funded for full system design manufacture and test. Two test tracks have been completed, a simple track in Bristol and a more complex figure of eight track in Cardiff with overhead and at-grade sections, and station loop. Testing has been in progress since April 2001. Two types of vehicles have been tested.

The National Assembly of Wales has voted funding to Cardiff County Council to install an operating ULTra system in Cardiff carrying its first passengers by 2005.

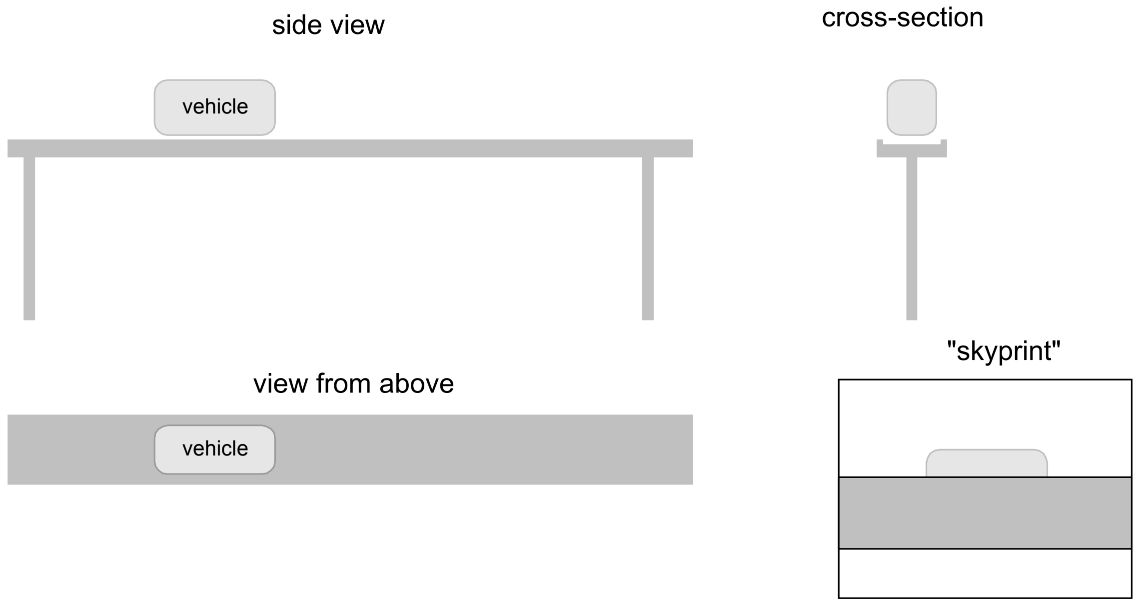
Evaluation

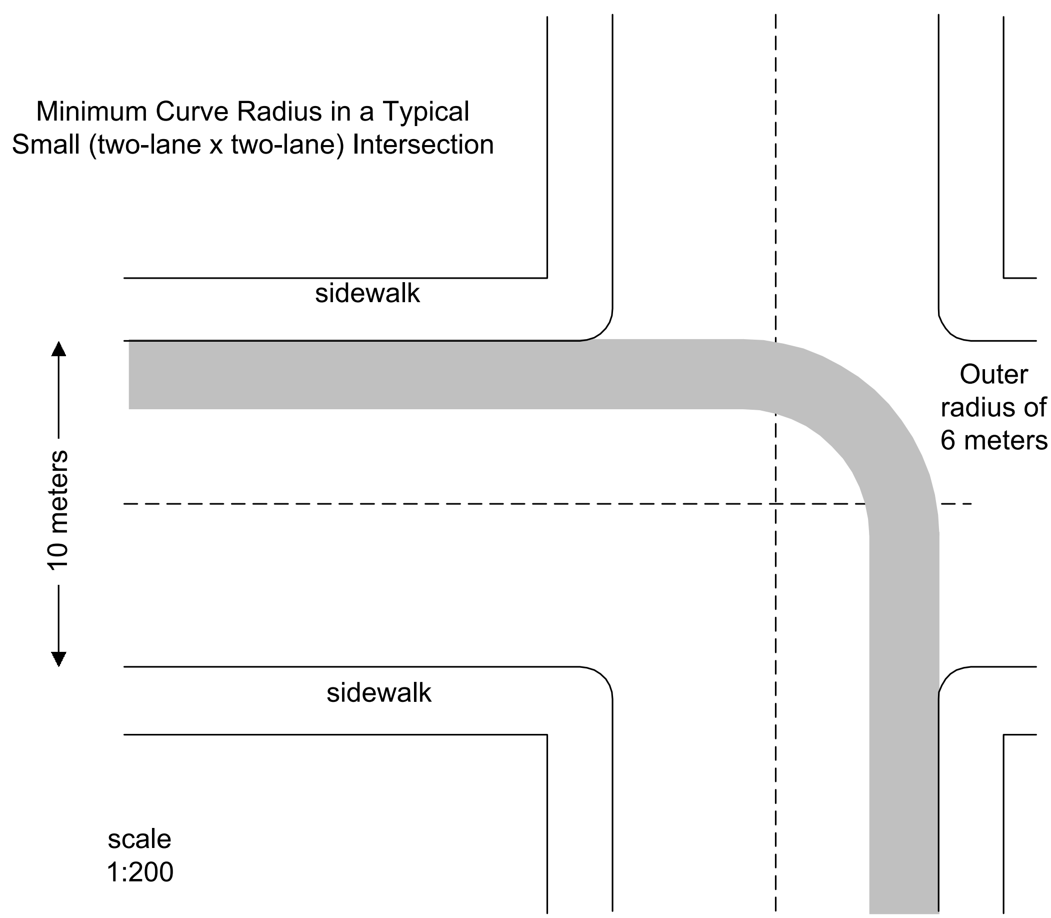
The system fell short on these evaluation points: (1) Vehicle separations are not reported. (2) There is only one motor in the vehicle. (3) Rail surfaces are exposed to the weather and so the system may have reduced traction when ice is present. This would influence the safe following distance (which impacts capacity), and could limit grade-climbing ability. (4) There is active guidance, without a passive safety steering feature. (5) The speed is slow, at 40 kph.

Summary: ULTra appears to be undergoing a rigorous development process, which is approaching completion. It appears likely that passenger service will be offered, as the necessary funding has been awarded for this. We have no reservations about its ability to perform as advertised, with the information we have available.



Ultra


side view
vehicle
cross-section
view from above
vehicle
"skyprint"


Minimum Curve Radius in a Typical
Small (two-lane x two-lane) Intersection
sidewalk
Outer
radius of
6 meters
10 meters
sidewalk
scale
1:200

Urbanaut

This vendor DID NOT REVIEW this report prior to publication.

Description

The Urbanaut guideway (or runway) is a flat surface with a narrow metal stabilizer rail (or fin) running along the center. The guideway is half the vehicle width. The thickness of the guideway is determined by structural considerations only.

Vehicles are car-like with 4 rubber tires. They ride on top of the guideway. The smallest vehicle seats 6. **WARNING**: Urbanaut is or may be marketing their system as a GRT system. However, for the purposes of this report, we are making the assumption that it could operate in PRT mode, in which case the vehicle would pick up only one passenger (or a group wishing to travel together) and make a non-stop trip to his or her destination. Please keep this distinction in mind if you compare the results of this report with Urbanaut literature.

Switching is accomplished by flexing the stabilizer rail.

Dimensions (m)	Height	Width	Length
Vehicle – small	2.0	0.75 (or 1.7?)	3.65
Vehicle – large		1.0	
Guideway	see notes	see notes	
Min. curve radius		38	
Skyprint	various		

A unique feature of Urbanaut is that the stabilizer rail is always the same size but guideways can be made at different widths. So even multiple system sizes for different applications can be linked, and the smaller vehicles can traverse the whole linked system.

Status

The inventor, Mr. Einar Svensson was one of the principal engineers with the Alweg Monorail Company,[9] of which 18 systems have been installed world wide.

Urbanaut has over the last 10-15 years invested several million dollars in the technology. 3 U.S. patents have been issued on vehicles, propulsion, switching and guideways. Patents have been applied for in many countries. No outside funding has been received in the U.S.

Extensive ProEngineering data, costs, including marketing analysis have been made for all aspects of the Urbanaut concept. A 1:10 Scale operational prototype technology center has been installed incorporating testing of all features, and design for future development and improvement.

Evaluation

The system fell short on these evaluation points: (1) The curve radius is very large. (2) Running surfaces are exposed to the weather and so the system may have reduced traction when ice is present. This would influence the safe following distance (which impacts capacity), and could limit grade-climbing ability.

Summary: Urbanaut is in the early stage of development. It is unclear what the depth and success of the engineering effort is to date.

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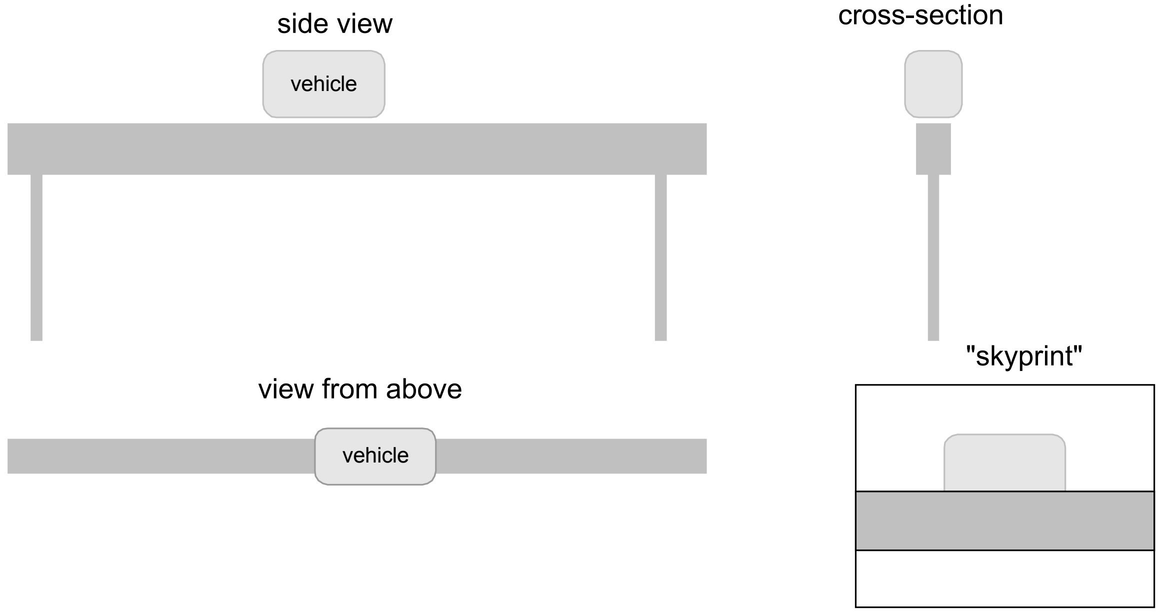
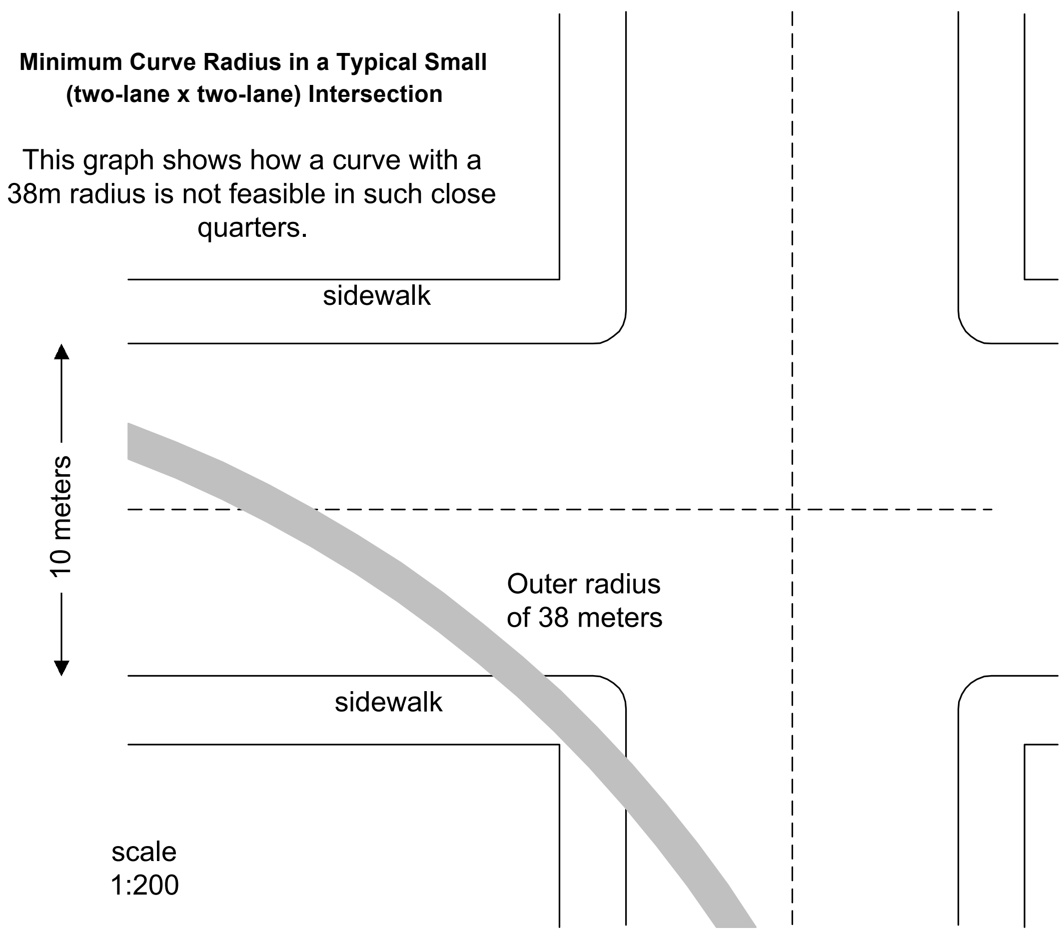
[9] Alweg is a 50 year old monorail concept that straddles a structural beam way that is an essential part of the system. In such a concept, the switching of guide ways involved flexing of a large massive beam way, which becomes cumbersome and expensive, and for this reason, this type of monorail has primarily been line oriented.

Urbanaut
(1/2 size vehicle)





Simple suspended systems

Higherway

This vendor REVIEWED this report prior to publication.

Description

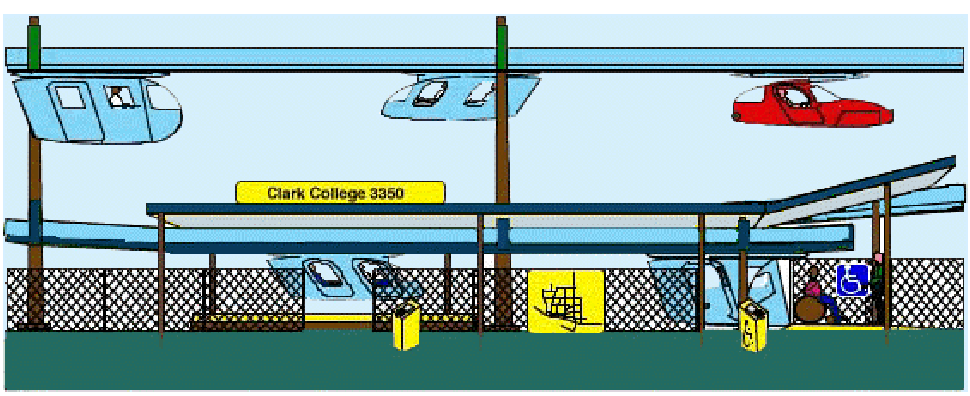
Higherway is a suspended technology offering PRT service, as will as dual mode vehicles. The guideway is roll-formed, corrosion-protected steel with an aluminum and stainless steel powerbar. It is formed into a shape that has a box-beam-type part (like several other systems) with various flanges and a utility duct added on in an integrated piece.

There are several models of vehicles in development; only the Dove (standard, 2 passengers) and Pelican (wheelchair accessible, 1 passenger) vehicles are mentioned in this report. Specially made dual mode cars and cargo carriers are also in design. The Dove has two seats, one in front of the other (tandem seating). Each rider has a separate door and automatic safety restraints.

Dimensions (m)	Height	Width	Length
Vehicle – Dove	1.8	0.8	4.5
Vehicle – Pelican	2.3	0.9	4.5
Guideway	1.0 [10]	0.44	22 m sections
Min. curve radius		5.5	
Skyprint	1.0		

Advantages noted by Higherway are:

- The pod to bogie mounting includes air suspension with weight sensing - too heavy loads are rejected.
- The pods can swing out on an axis inclined down toward the front. This reduces drag in cross winds and curves and improves stability.
- The tandem seating arrangement reduces frontal area which reduces guideway costs and the improved aerodynamics reduces the wind noise and the cost of power and power system initial cost.
- Having dual-mode cars and automated cargo pods which use the same carrier (Baz) as the ADA pod (Pelican) reduces costs and improves system utilization and profitability.
- Acceleration tracks parallel main arterial tracks - this assures that the main track can operate at capacity without being disrupted by accelerating vehicles, there is another alternate route for emergencies, and if a vehicle fails to reach arterial speed it can stay on the acceleration track and not slow traffic on the main track.



[10] On/off ramps have slightly smaller guideways at 0.65 m tall.

- Dynamically unstable steering, actively stabilized by a computer, makes a tight turning radius possible, reduces wear, and makes a better ride.

Status

Tad Winiecki, the inventor of Higherway, has a B.A. in Physics and an M.S. in Space Science. He is registered as a Colorado Professional Engineer, and is an experienced Manufacturing Engineer, Research Engineer and Systems Engineer. He holds five U.S. patents for motorcyclist crash protection inventions.

Less than 5 years and $5000 have been invested, plus unpaid time by the inventor, which could be valued at $100,000.

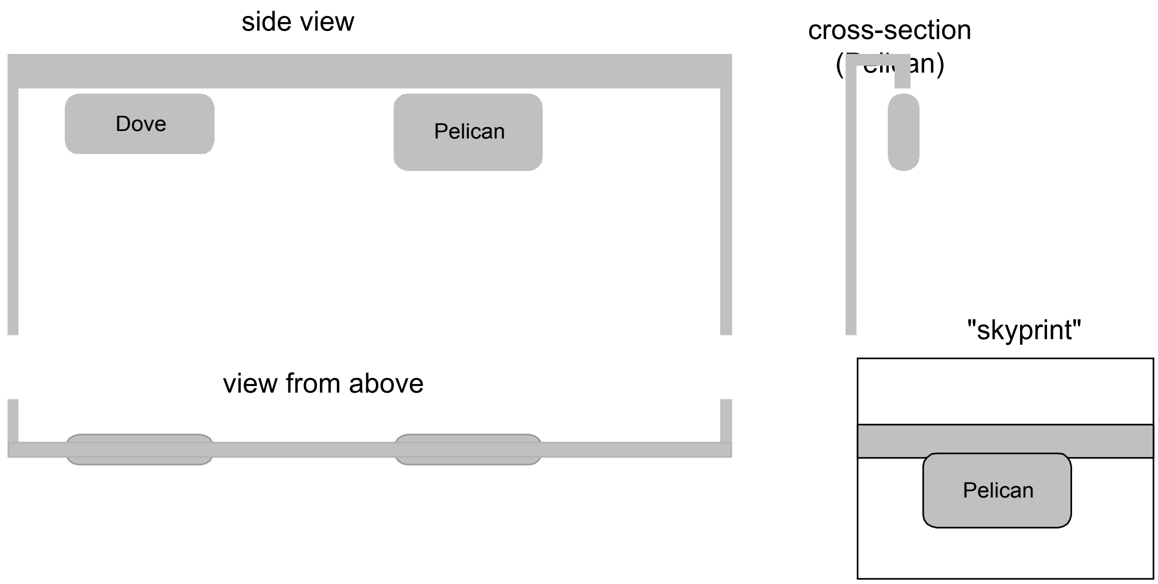
Evaluation

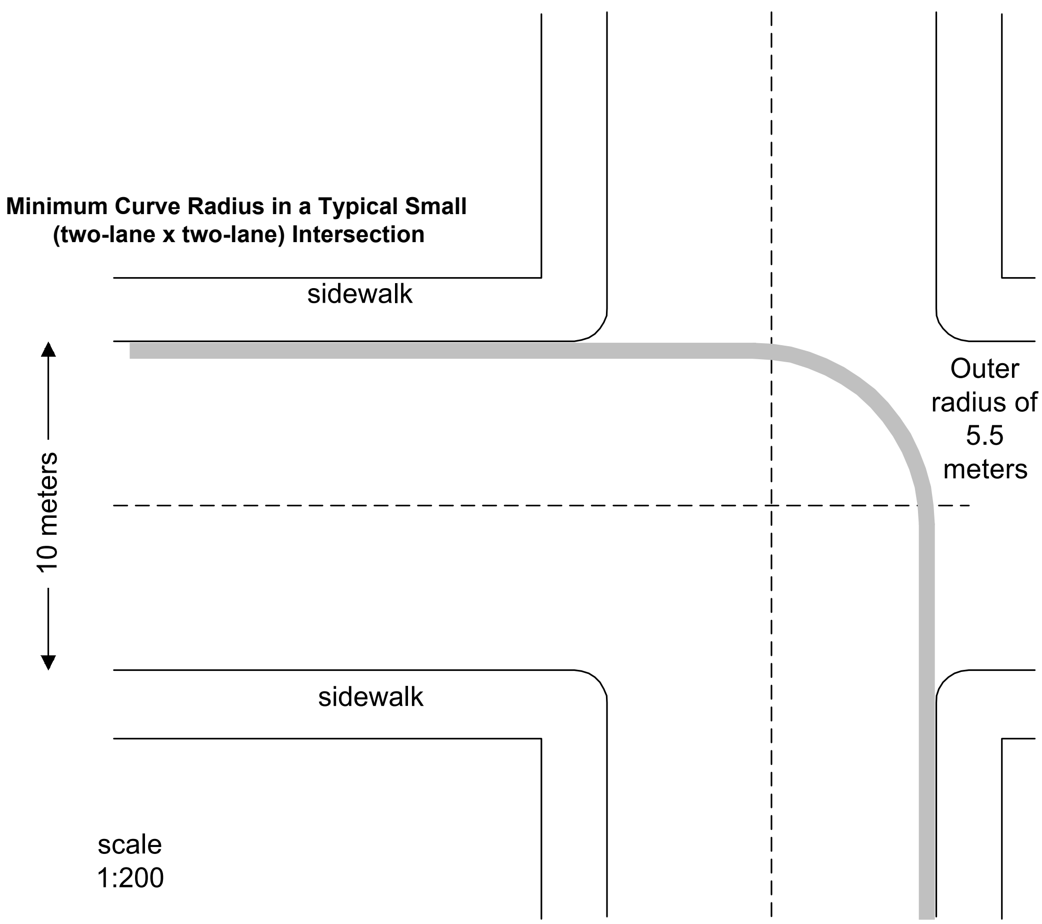
The system passed all evaluation points, at this early stage of development.

The design relies heavily on previous work by the Aerospace Corp., Taxi 2000 and Skytran.

Preliminary design and analysis have been performed, but the system is not fully engineered.

Higherway


side view
Dove
Pelican
cross-section
view from above
"skyprint"
Pelican


Minimum Curve Radius in a Typical Small
(two-lane x two-lane) Intersection
sidewalk
10 meters
Outer
radius of
5.5
meters
sidewalk
scale
1:200

Pathfinder

This vendor DID NOT REVIEW this report prior to publication.

Description

The Pathfinder guideway is a very small box beam with a narrow slit on the bottom. It is passive and unelectrified in most sections.

The vehicle holds up to 4 passengers. The power unit and wheels are inside the box beam, and the cabin hangs from a narrow support that passes through the guideway slot. The vehicle is battery powered and recharges in stations. Switching is done by the vehicle.

Dimensions (m)	Height	Width	Length
Vehicle	1.8	1.5	2.7
Guideway	0.5	0.4	
Min. curve radius		6	
Skyprint	0.6		

Status

Pathfinder's principals are Richard Hill, CEO (Tower International, Business consulting); Leonard (Jack) Locke, P.E Vice President; and Thomas Hallett, Vice President. Pathfinder is also supported by consultants: Burger ABAM Engineers (structural engineering and guideway); and Hamilton Engineers, Seattle Washington (Propulsion and Suspension).

Pathfinder Systems has been in development since the 1960's. During this time they have conducted engineering, marking studies and supported local governments in PRT feasibility studies. They estimate expenditures of over $2 million.

Quoting the company, "Pathfinder Systems has completed preliminary engineering and product definition studies. We are in position to begin a three-phase development program of component development, prototype assembly and test and production design and test, as funding becomes available. According to our 1998 studies, an initial system could, under the right conditions, be in service in about three years."

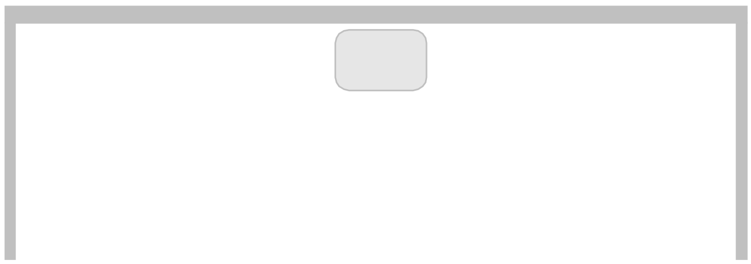
Evaluation

The system passed all evaluation points.

Summary: Pathfinder has started the engineering process but it is still early in development.

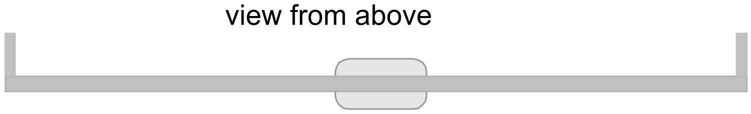
Pathfinder

side view

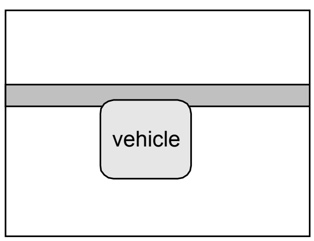


cross-section

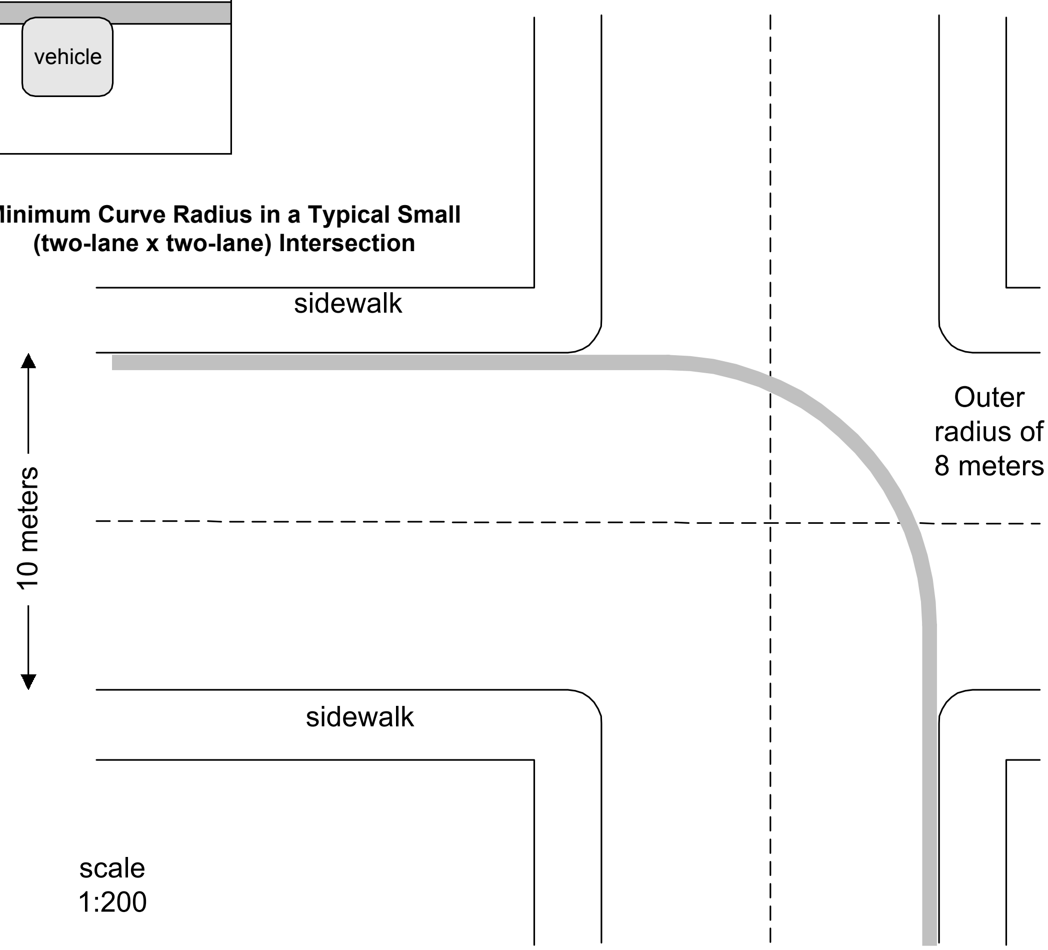
view from above



"skyprint"



Minimum Curve Radius in a Typical Small (two-lane x two-lane) Intersection



SwedeTrack

This vendor DID NOT REVIEW this report prior to publication.

Description

The SwedeTrack guideway is a box beam with a narrow slit on the bottom. Three sizes are proposed. Each size corresponds with a maximum vehicle width, a maximum load, and a diverse set of vehicle sizes.

The vehicles are composed of two or three parts that can be interchanged. The "drive wagon" (bogie, wheel set) is inside the box beam. An elevator component hangs from the drive wagon. The passenger or freight cabins hang from the elevators.

The vehicles range in capacity from one passenger on up to large vehicles.

SwedeTrack proposes using on-board elevators to lower cabins to the ground for boarding at stations. Operationally, this could involve an off line stop as proposed by the other systems, or the elevator could release the cabin on the ground and continue, stopping traffic only momentarily, and the cabin would be picked up by another drive wagon later on.

Dimensions (m)	Height	Width	Length
Vehicle			various
Guideway - small	1.1	0.6	
Guideway – medium	1.1	0.75	
Guideway – large	1.1	0.9	
Min. curve radius		6	
Skyprint – medium	1.3		

SwedeTrack proposes carrying cars on pallets as well as offering PRT and GRT service.

Status

The chairman of the board has worked 30 years with APMs, the CEO 10 years. The company is about 10 years old. Now 18 shareholders. A board of 10 persons. An executive group of 3 persons.

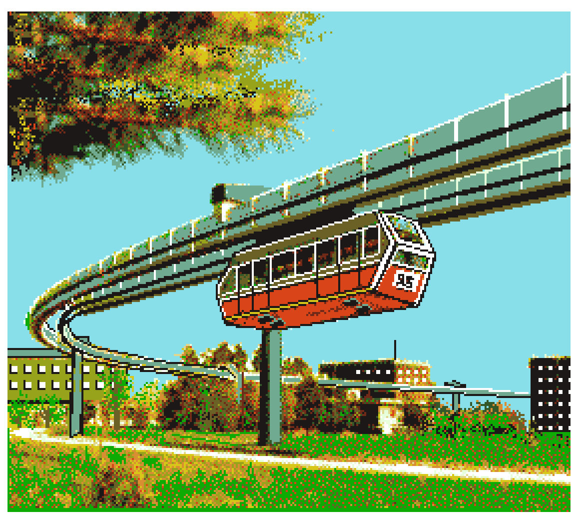
Funding has been received from the city of Gothenburg, Stockholm and the Information Technology Delegation.

The team is working with the Swedish MegaCity Project. The first phase consists of a technology test track in about one year, the second phase of a demonstration net of about 20 kilometers in about 3 years, and the following phases of stepwise additions of nets in other parts of the city. The goal is to cover the whole MegaCity at about year 2015.

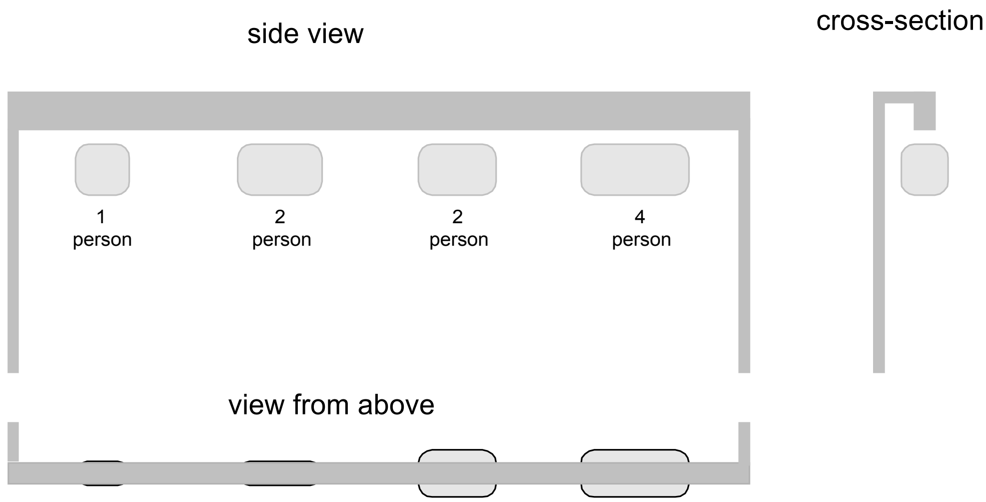
Evaluation

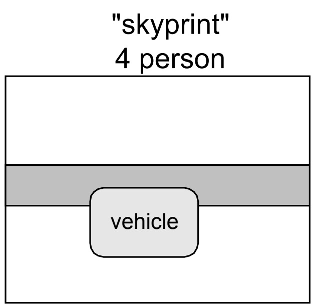
The system passed all evaluation points, at this early stage of development.

Summary: SwedeTrack is in preliminary design, or more appropriately, concept definition.

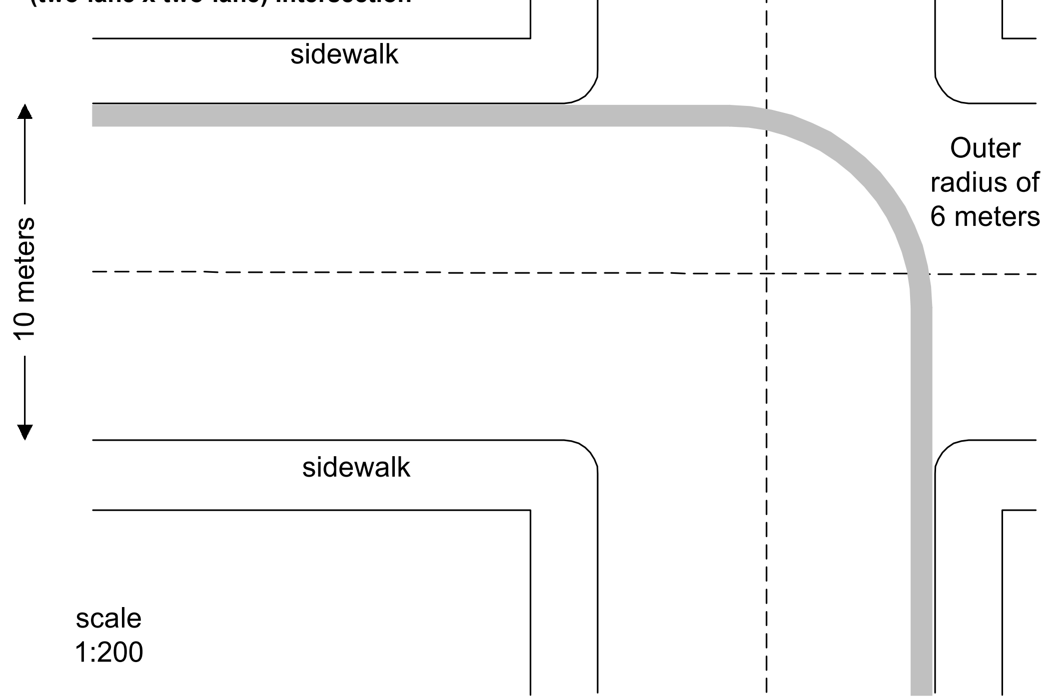


SwedeTrack





Minimum Curve Radius in a Typical Small (two-lane x two-lane) Intersection



Other systems

Frog

This vendor REVIEWED this report prior to publication.

Description

Frog is a technology that can be used to provide PRT service, but its primary intention (at least initially) is to provide feeder service to existing mass transit stations. Unlike some other systems, Frog is intended to be viable in very small applications, such as a single parking lot. Vehicles drive on a standard road surface with no physical guidance at all. Extensions of the track can easily be realized by adding reference points to the track (magnets) and editing the layout in the supervisory computer. Mixing with other traffic will become possible in the long run using this technology, but not at present.

Since this report is only concerned with PRT service, Frog will be assumed for comparison purposes to be using a dedicated guideway that has no grade crossings with other traffic, and may be built elevated. When elevated, there would be safety curbs to prevent a malfunctioning vehicle from driving off the track. In the drawing following, the size of the guideway and skyprint was estimated by the committee, not provided by Frog.

The vehicle is basically a car or bus with automatic driving capability.

Dimensions (m)	Height	Width	Length
Vehicle – ParkShuttle 20 passenger	2.1	2.45	5.5
Vehicle – ParkShuttle – 10 passenger	2.1	2.45	4.5
Vehicle – CyberCab – 4 passengers	1.7	1.4	2.5
Guideway	N/A	vehicle width + 0.4 m	
Min. curve radius – ParkShuttle		13.5 [11]	
Min curve radius 0 CyberCab		9	
Skyprint	various		

Status

The Frog team has an academic background and many years of experience with electronics, guidance, data-communication, vehicle engineering, software development and other expertise involved.

Development of the technology started in 1984. Development of the vehicles for people transportation started in 1995. The development department is constantly upgrading the hardware and software. The number of man-years and the development costs are confidential.

SuperFROG, the control system, has been totally developed and operational for over 10 years for indoor industrial applications and outdoor industrial and people mover applications.

Two pilot projects, with a total of 7 vehicles seating 10 passengers each, have been installed and have been operating since 1997 and 1999 respectively. One of these pilot projects will be continued and expanded with new, second generation vehicles in 2003. Another system will be installed in the beginning of 2002,

[11] Radius is reported as "between walls", i.e. the outer part of the curve made.

using vehicles seating 4 to 6 passengers. For this system two prototypes have been built for testing purposes. In total 25 vehicles will be operational at this site.

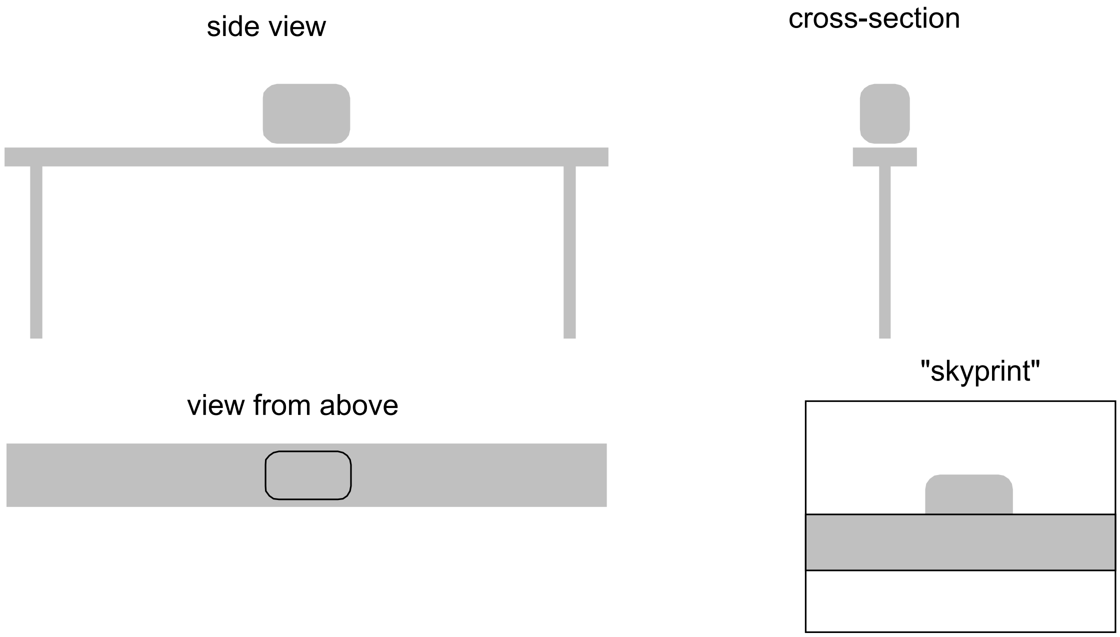
Evaluation

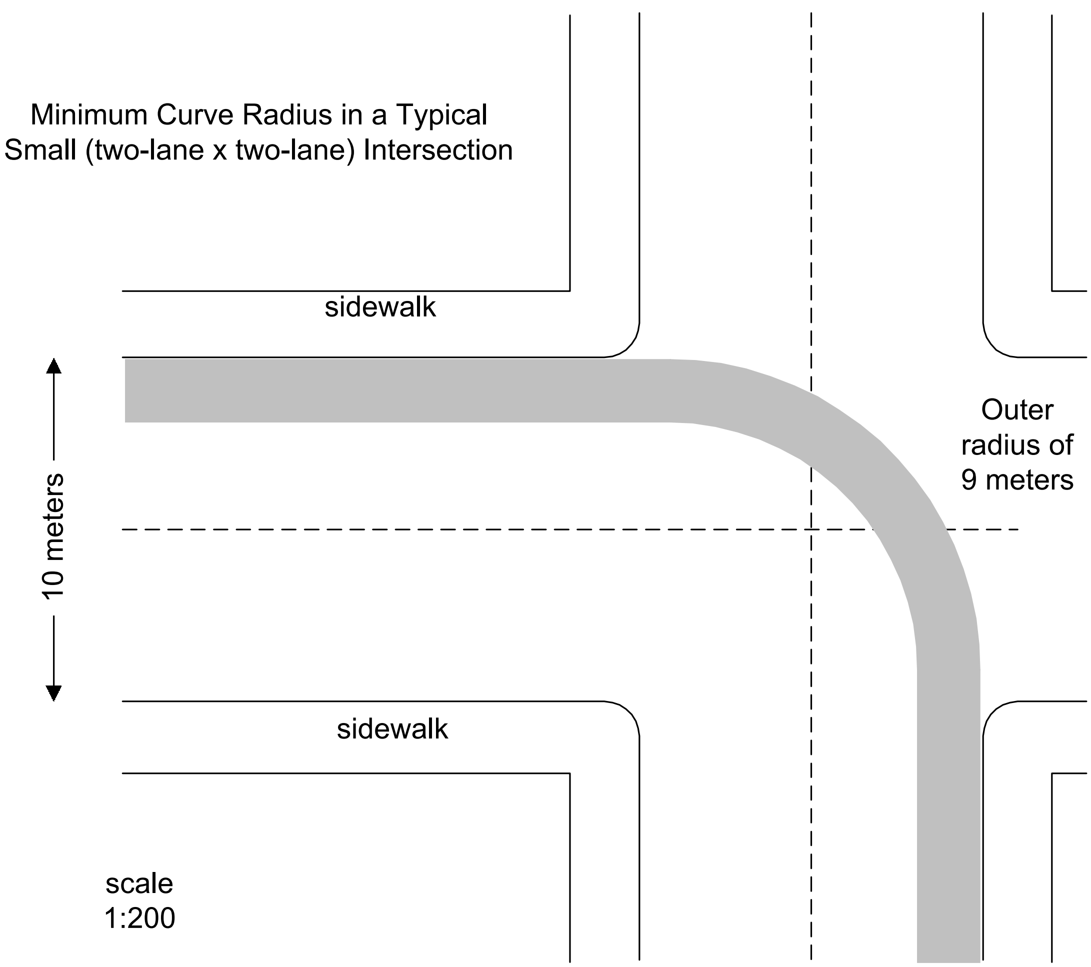
The major obstacle to implementing Frog as PRT is that its originally intended market niche is apparently to serve ground level short-distance group transit needs exemplified by parking shuttles. In order to be used as PRT, the smaller vehicle would be used, and grade-separated roadway would be built. This would be doable but is apparently not the company's current focus.

The system fell short on these evaluation points: (1) There is only one motor in the vehicle. (2) Rail surfaces are exposed to the weather and so the system may have reduced traction when ice is present. This would influence the safe following distance (which impacts capacity), and could limit grade-climbing ability. (4) There is active guidance, without a passive safety steering feature.

Summary: Frog may be undergoing a rigorous development process, which is not yet complete. However, we do not have enough details to be able to evaluate their level of effort and success to date. The company has a transit system in operation, but not offering true PRT service.

FROG


side view
cross-section
view from above
"skyprint"


Minimum Curve Radius in a Typical
Small (two-lane x two-lane) Intersection
sidewalk
10 meters
Outer
radius of
9 meters
sidewalk
scale
1:200

MAIT

This vendor DID NOT REVIEW this report prior to publication.

Description

MAIT is a company that will not actually provide a PRT system, but is designing a standardized vehicle transfer mechanism that will allow a passive cabin to move among many different, separately developed, transport carriers.

The carriers could be low speed or high speed, entrained or not. They could be road trucks, automated guideway carriers, or any other vehicle type. The thing in common with all carriers is their attachment mechanism.

The loads, or charges, could be passenger cabins or freight containers. They could also be designed in many different ways, but would have a standard attachment mechanism.

In this way, any load could theoretically be moved by any carrier, even if designed separately and never tested together. A journey might consist of any number of mode changes, which would each be automatic and unimportant from the passenger's point of view.

The company also is developing simulation software that allows the design and evaluation of the performance of various PRT and AGV systems in isolation and in combination.

Advantages listed by the company include:

- Cabins can be taken off-line and stored. The capital cost of cabins will be low compared with the other components and this will allow greater overall efficiency of the system. For example, cabins carrying goods can be loaded and unloaded at leisure while the carrier can go back into service immediately. Similarly, where there is a tidal flow of traffic, perhaps due to commuting into an urban center, there can be many more cabins than carriers and they can be accumulated at either end of the flow.
- Cabins with different internal fittings and for passengers and goods can travel around the same system.
- Cabins can be owned by individuals, companies or local authorities.

MAIT is not included in many of the evaluation sections in this report because it is not in itself a complete PRT system.

Status

The small MAIT team, which apparently consists of two collaborating private inventors, has a background that includes mechanical and control systems engineering. Their policy is to collaborate with other bodies to access all the diverse skills that will be needed.

There has been no funding, but the efforts of Joerg Schweizer amount to about $100k in value.

Quoting the vendor: "MAIT is a concept that can be applied to most proposed PRT systems and will integrate them into a unified transport structure. The objective of the developers is to concentrate on the aspects of the system that are peculiar to the concept. So far this has included a formal bottom-up definition of the system, a more specific engineering specification of the attachment mechanism (in preparation for a major funding application) and development of a core for integrating the various control software of the component systems."

From the point of view of a municipality or other PRT customer, MAIT is not a direct vendor, but instead a vendor and collaborator with other PRT system developers.

Ruf

This vendor REVIEWED this report prior to publication.

Description

Ruf is a dual mode system offering both individual cars and busses (called maxi-rufs). Unlike any other system evaluated in this study, Ruf is pure dual mode, as opposed to PRT with a dual mode option. In order to include Ruf in this report, we are evaluating it solely on the basis of how well it can perform in PRT mode, which is not its primarily intended usage. The system may suffer in this evaluation because of that mismatch of goals.

The Ruf monorail guideway cross section is a triangle with the flat side on the bottom and pointed on top. The guideway is passive and contains no switches.

The vehicles have a triangular (prism-shape) cutout on the bottom which fits the guideway. Vehicles have two sets of wheels. The road wheels are standard auto tires. The guideway wheels make contact with both sides of the triangular guideway. Externally only the road wheels are visible. The guideway shape facilitates the transition from road driving to guideway driving, without having to stop.

A Ruf network consists of disconnected stretches of guideway. Switching is accomplished by leaving the guideway and using the road wheels on a flat switching area, then re-mounting another guideway stretch. The driving of the vehicle in a switch section is automated, so that no manual driving is performed anywhere in the network.

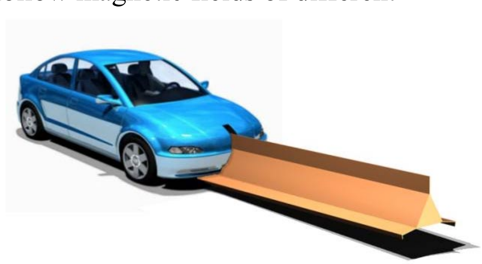
When used as dual mode, Ruf could be built with no stations at all, just exit ramps that would deposit traffic onto city streets. When used as pure PRT or a mix, there would be stations.

WARNING: Ruf is marketing their system as a dual-mode and GRT system. However, for the purposes of this report, we are making the assumption that it could operate in PRT mode, in which case the cars would pick up only one passenger (or a group wishing to travel together) and make a non-stop trip to his or her destination, without leaving the guideway. Please keep this distinction in mind if you compare the results of this report with Ruf literature.

Dimensions (m)	**Height**	**Width**	**Length**
Vehicle – Ruf	various	various	3.5
Vehicle – Maxi-ruf	2.0	2.0	7.0
Guideway	0.58	0.85	20 m sections
Min. curve radius		26	
Skyprint	0.7		

The company notes these additional features:

- RUF is a dual mode system. This means that the vehicles are more complex, but also that the system offers some essential advantages such as door-to-door transport, possible private ownership and design variations.
- The RUF system creates trains if the distances between switches is long.
- The switch uses on board sensors who make the ruf follow magnetic fields of different frequencies.
- The ruf can be equipped with a hybrid unit when it is not using the guideway. With this unit mounted in the empty slot under the ruf, it can drive anywhere a car can drive and refill at any gas station.



- The triangular rail ensures a very high stability because the center of gravity is placed below the top of the rail. This configuration makes derailment impossible.

- Articulated bus configuration of up to 3 maxi-rufs are possible because of the coupling units being an integral part of all vehicles. This means that the bus part of the system can match the demand better than normal busses.

Status

The engineering team for Ruf consists of people from different companies working together at the University for Applied Sciences in Copenhagen, and with support from university professors.

RUF has been under development in Denmark since 1988. It has been funded by private and public money. The total development cost so far is in the order of magnitude of $1.5 million.

Two EU programs are now supporting RUF with additional funds:

- CyberCars - Information Society Technology - 120,000 EURO
- CyberMove - Energy, Environment and Sustainable Development - 110,000 EURO

A fully functional test track and a 1:1 operating Ruf has been built and is currently being tested at the University of Applied Sciences in Ballerup outside Copenhagen, Denmark. The test vehicle is able to show most of the basic functions of a Ruf, but more development is still needed.

A 1:1 mock-up of the maxi-ruf has been built and a 200 m expanded test track has been planned and prepared for. The ground is available and ready and the material has been donated by the Danish Steel Works, so it is ready to be erected.

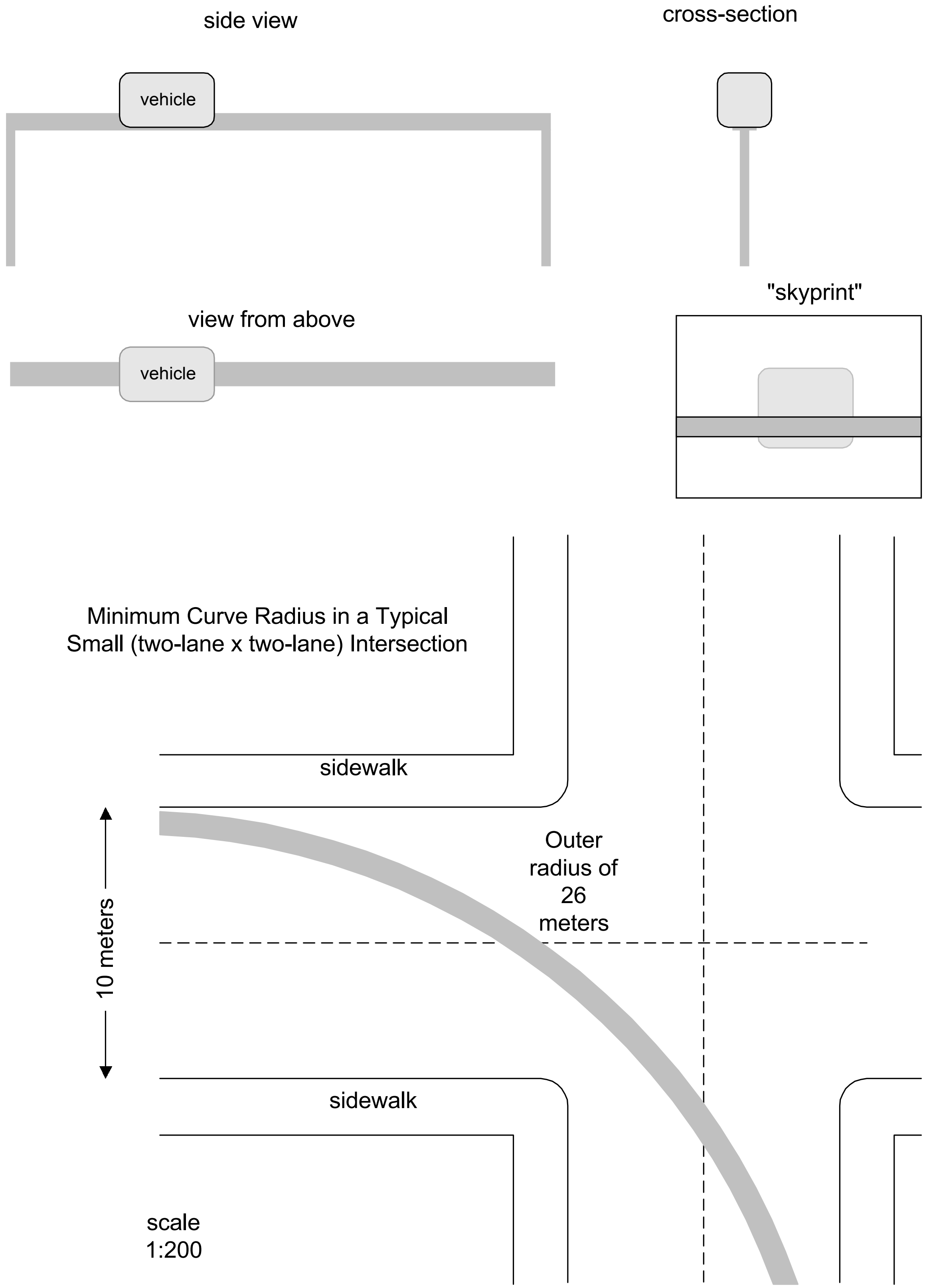
Software has been written for simulations, travel demand and flow, and energy use.

Evaluation

The system fell short on these evaluation points: (1) The curve radius is marginal. (2) Rail surfaces are exposed to the weather and so the system would have reduced traction when ice was present. This would influence the safe following distance (which impacts capacity), and could limit grade-climbing ability. (3) There is active guidance in switches, without a passive safety steering feature.

Summary: Ruf is in the early or middle stage of engineering and appears to be undergoing a rigorous development process.

RUF


side view
cross-section
vehicle
"skyprint"
view from above
vehicle
Minimum Curve Radius in a Typical
Small (two-lane x two-lane) Intersection
sidewalk
Outer
radius of
26
meters
10 meters
sidewalk
scale
1:200

Evaluation of visual/geometric factors

Curve radius

Urbanaut, at 38 m, does not meet the suggested requirement of 20 m curve radius.

Ruf is marginal at 26 m. (The diagram shows how it *could* work in an intersection)

All other systems have the option of a small curve radius. (Of course they will use larger radii wherever possible to keep speeds higher.)

Skyprint

The largest skyprints are Cybertran (3.0 m) and Autran (2.3 m). These might be too visually obstructive for dense urban areas, but not by a large margin, and still much less obstructive than non-PRT alternatives like light rail.

These systems have exceptionally small skyprints of 1 m or less: Higherway, Mitchell, Pathfinder, and Ruf.

All the other systems have good skyprints of between 1 m and 2 m. (MegaRail has an interesting shape because the rails are thin but tall. Viewed from directly below, the skyprint is very small, but from the side it is large.)

Geometric flexibility

All systems allow close station spacing and switched networks, which is inherent in the definition of PRT.

Information on guideway spans was not obtained from all vendors, so we are not evaluating this.

How development status relates to other factors

We thought that vendors with greater funding might have higher cost estimates, because of the phenomenon that things seem simple at first and always get more complicated the more you get into them. However, we found no such correlation, which adds to the credibility of the cost estimates.

Evaluation of development status

The bottom line is that you cannot purchase a working PRT system off the shelf today, because all the vendors specify that they need more development funding, and there is no manufacturing currently being done of the vehicles and guideways. However, several vendors use mainly off-the-shelf components, so manufacturing prep time could be quite short.

On the engineering front, despite the fact that it isn't quite done, it is encouraging that all the pieces seem to have been developed and that there are a lot of parallels among the separate efforts. The remaining large step is to build a working system with more than a handful of vehicles. All the prototypes built so far have been too small to qualify as realistic tests of a control system. (Cabintaxi is an exception.)

But instead of just saying that it isn't ready, we will go on to explore how it can *become* ready. There are two main gaps that exist between the vendors and customers, even before it makes sense to complete the engineering.

The first gap is policy: If a city wanted to purchase a PRT system, the city and state would have to come up with a new set of regulations covering rights of way, visual rights, liability, safety, and a long list of factors for which there are no current regulations, and that are not on government agendas currently. Also, the city would have to know *how* to buy a system: what requirements would be reasonable to place on a vendor? Policy is related to engineering, because the vendors are currently *guessing* what the requirements would be, and developing according to those guesses. If governments were able to participate actively in specifying requirements, particularly around property protection and easements, safety, and accessibility, then the vendors could proceed with clearer goals and change their designs to fit exactly what the public stated that it wanted. The effort required to close the policy gap is potentially much larger than the effort of PRT vendors to redesign systems to meet clear requirements. So, in this area, the engineering isn't the main issue.

The second gap is investment risk, which is related to policy. No matter how clear is the argument that PRT can be profitable, if there are no clearly defined lines between the responsibility and ownership by the city, the operator, and the technology supplier, there is no protection for an investor. Once these lines are established through contracts and regulations, private investment money becomes more protected, and therefore more available.

Based on their knowledge of the technical and social issues, the majority of the report team feels that PRT is technically viable and will deliver on its promises once implemented. The main obstacles seem to be in the marketing, rather than technical realm. We believe some of the systems are ready for full scale demonstration projects for practical use. In fact, ULTra is embarking on such a project at the time of this publication.

We promised the vendors not to publish any points or ranking of the systems, but this does not mean that we are trying to "equalize" them. Of course, some systems are much further along in their engineering than others.

Guideway Structure

Evaluation criteria

- Beam stiffness, strength, etc. engineered properly for local conditions (such as earthquake zone).
- Life expectancy is 50 years, with justification.
- Vehicles captive to guideway, which is reserved for the vehicles.
- (Requirement for strength of supports is listed under safety section.)

Evaluation

The committee recognizes that guideway structure is a vital and factor in design and is the dominant cost component of the system, but does not have the capability of evaluating it.

The requirement that vehicles are captive to the guideway is met *absolutely* by most systems, and can be met *functionally* by all systems. Certain systems (Cybertran and Frog, for example), would permit a hypothetical upward force to lift the vehicle from the guideway because it is not physically attached, but the guideway could be built with appropriate barriers to make it operationally captive. We don't believe this issue is significant, and it is only mentioned to clarify our interpretation of ATRA's prior definition that PRT is "captive to the guideway."

Vehicle, passenger comfort

Evaluation criteria

- Vehicle is wheelchair accessible.
- Vehicle has capacity of at least 2 people.
- Vehicle has climate control system (either fixed temperature or adjustable).
- Vehicle has inside lighting.
- Ride quality is comparable to trains or better.
- System is designed to remain level or bank no more than about 25 degrees.
- Internal noise is low. 68 dBA or less is acceptable; 50 dBA or less is good.
- Under normal operations, maximum acceleration and deceleration is about 0.25 g (2.45 m/s/s), but emergency braking may be designed for up to 0.8 g deceleration.[12]
- Cabin size accommodates bicycle, baby carriage.
- Seating for available for all passengers, no standing ride.
- Passengers can see out front and side of cabin during ride.
- Electronic communications are available.

Evaluation of wheelchair accessibility

All vendors proposed wheelchair accessible vehicles. These vendors proposed that all vehicles and the entire system would be equally accessible:

Autran
Cybertran

[12] See evaluation section for objections to this acceleration requirement.

MAIT
Pathfinder
Taxi 2000
ULTra
Urbanaut

However, other vendors, listed below, proposed that only some vehicles would be accessible, apparently for cost savings:

- Higherway – Dead-end berths for Pelican pods (accessible) are adjacent to berths for Dove pods (normal). There are wheelchair ramps with fences so that wheelchair users can back into the Pelican pods thru the front door. The Pelican pods lock onto the ramps with essentially no gap or step for the wheelchairs to cross.
- MegaRail – PAT (PRT) and GAT (GRT) cars can handle non-electric wheelchairs, but heavier electric wheelchairs require dispatch of a special vehicle.
- MicroRail – Requires dispatch of special vehicle.
- Mitchell – All vehicles are wheelchair accessible in their ADA system, but they can also deliver a smaller non-ADA system if wheelchair accessibility is not needed – see Vehicle size chart below.
- Ruf – Only Maxi-Ruf (GRT) is accessible. The front seats are tilted up to make floor space for a wheelchair. A wheelchair lift has been constructed in order to enable the disabled person to use the Maxi-ruf without help from others. By means of a electronic device, the disabled person can lower the lift and drive on to its platform. While facing forward all the time, the person is lifted and placed between the two front seats.
- Swedetrack – Only some vehicles are accessible

In conclusion, all systems studied adequately meet the accessibility requirement.

Accessibility notes

- In the case of a special accessible vehicle, some system would be needed to ensure the same overall level of service for those needing such a vehicle. This could involve having a sufficient empty accessible vehicles circulating, or storing them close by, or prioritizing their routes.
- Manual shutting of the door is proposed by at least one system, and this may not be possible for some disabled passengers. On the other hand, manual shutting is a benefit in the area of ensuring that a real person is the passenger (rather than a bomb, for example).
- **Blind:** Multiple vendors proposed ways to handle special needs of the blind, such as textured paths to the berths that will aid blind people, and vehicles which talk to announce who they are ready to carry and when they arrive at the desired berth.
- **Deaf:** Multiple vendors proposed ways to handle special needs of the deaf, such as visual displays on the vehicles that convey boarding information.
- Taxi 2000 proposed that wheelchairs can be oriented sideways, and that this represents a cost savings.

Evaluation of vehicle size

All vendors meet the basic requirements of 2 seated passengers. Additional benefits and notes are in the following table.

The WEIGHT column lists the empty vehicle weight followed by the maximum gross weight.

Vendor	Vehicle model	Num passengers seated	Num passengers plus (1) or (2) wheelchairs[13]	Weight (empty / max, kg)	Notes
Austrans	standard	9	7 (1)	?	GRT
Autran	PRT	4	2 (1)	?	
Autran	GRT	8	6 (1)	?	GRT
Cybertran	smallest[14]	6	6 (2)	3200 / 4500	GRT
Cybertran	largest	20	20 (2)	3200 / 4500	GRT
Frog	ParkShuttle 20	12 +13 standing	10 (2) + 8 standing	3000 / 5000	GRT
Frog	ParkShuttle 10	10 + 4 standing	8 (1) + 2 standing	2500 / 3600	GRT
Frog	CyberCab	4	2 (1)	800 / 1160	
Higherway	Dove	2	N/A	200 / 400	
Higherway	Pelican	1 [15]	1 (1)	400 / 800	
MAIT	standard	4	4 (1)		
MegaRail	PAT (PRT)[16]	6	2 (1)	1200 / 1800	or 4 + tables
MegaRail	GAT (GRT)	12	10 (1) or 8 (2)	1300 / 2500	or 8 + tables
MicroRail	PAT (PRT)	4	2 (1)	400 / 800	
Mitchell	standard	2	N/A	90 / 300	
Mitchell	accessible	4	1 (1)	135 / 500	
Pathfinder	standard	4	?	?	
Ruf	Maxi-ruf	10[17]	6 (2)	2500 / 3500	GRT
SwedeTrack	1-pass[18]	1	0 (1)	2200 / 3500	
SwedeTrack	4-pass	4	2 (1) ?[19]	?	
Taxi 2000	standard	3	1 (1)	455 / ?	single bench
ULTra	standard	4	2 (1)	?	
Urbanaut	single	6	6 (1)	500 / ?	GRT
Urbanaut	double	12	12 (2)	900 / ?	GRT

<u>Vehicle size notes</u>

- Those vehicles with 6 or more seats are labeled "GRT", and generally speaking, the vendors of these systems are marketing the systems as Group Rapid Transit. However, for the purposes of this report, regardless of how they are marketing their systems and the vehicle sizes, we are treating the systems as if they all operate in PRT service mode, carrying one passenger at a time or a group wishing to travel together.
- Accessible vehicle types could also be used for bicycles or baby carriages.
- We did not request vehicle capacity in weight, inside dimensions, or the size of each seat, and it is likely that different vendors assumed different passenger-plus-baggage weights and seat sizes.

[13] The wheelchair capacity column should be read as follows: "2 (1)" means two seated non-wheelchair passengers PLUS one wheelchair.
[14] Cybertran specifies a variety of seating arrangements from 6 to 20. All arrangements have the same size body, hence the same empty vehicle weight.
[15] The Pelican holds one adult and has two fold-down seats for children.
[16] PRT service mode is planned for the smaller 6-passenger MegaRail vehicle.
[17] Each Maxi-ruf seat is a separate seat, not bench-type seating. Each seat has its own door.
[18] SwedeTrack specifies a large variety of sizes from 1 to 32 passengers.
[19] All seats are foldable to allow a variety of wheelchair placements. Wheelchairs are only fully supported by the middle and larger beam size, not the small beam size. For equal service to the disabled, the small beam size would have to be completely ruled out.

Evaluation

Vehicle weights are generally reasonable and in the range of 100 to 200 kg per seat (empty). However, Urbanaut and Ruf claim a much lower weight target (under 100 kg per seat), which could require further justification to be credible. Mitchell has a low weight, but has no on-board motor. The 6-passenger CyberTran weighs in at 533 kg per seat, but these are large first class seats occupying the space of three regular seats. (The 20 passenger version, with smaller and lighter seats, weighs in at 160 kg per seat.)

Passenger capacity ranges from 1 to 20. Some vendors have pointed out that their studies indicated no substantial savings in decreasing vehicle size below 3-6, so a 1- or 2-passenger vehicle may have no particular benefit. A vehicle holding 6 or more passengers would very rarely be used to capacity in PRT mode, and those larger ones are probably intended for GRT service.

Evaluation of ride quality and noise

Banking

Very little information was available about banking, so we won't evaluate it here. It is noted that all suspended systems feature passive banking in curves, perhaps without the need to bank the track itself. Taxi 2000 also supports banked curves (supported).

Accelerations

These systems reported normal accelerations in the range 0.2 – 0.25 g: Autran, CyberTran, Ruf, MegaRail, MicroRail.

Frog reported a lower acceleration of 0.1 g, and even less when going up hill, but normal deceleration of about 0.3 g.

Mitchell and Higherway reported 0.5 g, which would be beyond a comfortable limit for normal operations, according to traditional transit approaches. However, 0.5 g is common in airplanes. If permitted, these higher accelerations could reduce the length and cost of on-ramps.

Other systems did not respond.

Emergency decelerations would of course be higher.

Internal noise

Very little information was available, so we don't evaluate internal noise here.

Evaluation of views

Window placements are as follows:

Side only	Side and front	Side, front, and rear
Maxi-Ruf MegaRail[20] MicroRail	Autran CyberTran Higherway Mitchell	Ruf Frog

[20] No windows are on the front of MegaRail and MicroRail because the ends have emergency egress doors.

The need to see out the front is reduced for larger vehicles such as Maxi-Ruf, where greater area of side windows partially compensate for lack of a front window. Maxi-Ruf is intended for GRT service, so is less relevant for the purposes of this report.

MegaRail and MicroRail are therefore the only systems that appear to fail the suggested requirement of front and side views.

Evaluation of electric passenger amenities

We estimate that electric passenger amenities can be added at customer request, and that no system is inherently incapable of providing the desired features. These features would be: climate control, lighting, and PC networking/communications. Some vendors said their vehicles would have internet access and various communication setups, and other vendors didn't mention these features, but we are not including that information, because any system could have these features as well as any other.

Passenger amenities imply an electric load in the vehicle. Since all systems except one transfer power to the vehicle for propulsion, it is clear that a portion of that power can be used for these other needs. In the case of Mitchell, which does not transfer power to the vehicle for propulsion, the system charges in-vehicle batteries from a third rail which is present only in stations. The batteries can deliver up to 500 W for amenities.

Propulsion system, grade, traction

How propulsion relates to other factors

Propulsion relates closely to ride quality factors, which are listed in the vehicle and passenger comfort section.

Propulsion and traction also relate to the control system and headways, and therefore to the system capacity. The inherent traction of the propulsion system affects the ability of the control system to control close vehicle spacing precisely, and to stop vehicles quickly when necessary under failure conditions.

Propulsion also relates to all-weather reliability; for example, vehicles with redundant motors would be more reliable than vehicles with an equivalent single motor. Reliability is covered in a separate section.

Evaluation criteria

- System can be operated in conditions of rain, snow and ice.
- System has grade climbing ability to match area of installation, 10% minimum.

Description of propulsion systems

There are several different kinds of motors and drive systems proposed, classified as follows:

1. in-vehicle rotary motors using power continuously supplied by the guideway (most systems)
2. in-vehicle rotary motors using battery power, with a system for recharging batteries (Frog, Pathfinder, and ULTra)
3. linear motor, with passive side mounted on guideway and powered side mounted on vehicle, using power continuously supplied by the guideway (Taxi 2000)
4. guideway-mounted motors that physically push the vehicles (Mitchell)

Some tradeoffs involved in the propulsion system include:

- Guideway-based propulsion may give better traction and positioning control to make short headways safe. In the case of LIM (see Taxi 2000 below) propulsion, traction is not relevant, because speed control is magnetic, not physical through the wheels.
- Guideway-based propulsion makes the vehicles cheaper and guideway more expensive, which makes the overall cost per service rendered DECREASE as the traffic density increases. Vehicle-based propulsion makes the vehicles more expensive and the guideway cheaper, which makes the overall cost per service rendered INCREASE as the usage increases. However, at low usage levels, vehicle-based propulsion would be cheaper (if all other elements could be equal).[21]
- The electronic controls are obviously different for different propulsion systems.

Systems using rotary motors

All these systems use rotary electric motors. Since they have similarities, they can be best explained with a table. In general for all these systems, the control system instructs the vehicle what speed it must approach, and the motors receive variable power as necessary to achieve the control speed and maintain proper spacing.

System	Type of motor (AC/DC, Volts, etc)	Method of power pick up	Number of motors/ number of drive wheels	Material of wheels/running surface	Max Grade (%)
Austrans	AC	?	2/4	?	?
Autran	440VAC	contact	1/4 [22]	steel/steel	10 [23]
Cybertran	600 VDC	contact	2/4	steel/steel	20
Frog	96VDC	battery[24]	1/2	rubber/concrete	10 [25]
Higherway	600 VDC [26]	contact	2/2	rubber/steel	20 [27]
MAIT [28]	N/A	N/A	N/A	N/A	N/A
MegaRail	880 VAC (3 phase)	contact [29]	4/4	rubber/steel	10[30]
MicroRail	880 VAC (3 phase)	contact	4/4	rubber/steel	10
Pathfinder	48 VDC	battery – recharge in stations	2/2 or 4/4	?	?
Ruf[31]	132 VAC	contact[32]	2/2	steel/rubber[33]	20

[21] Mitchell claims that vehicle-based propulsion would *not* make the guideway cheaper, because it would have to be stronger to support the extra weight of the vehicles' motors. Please refer to the cost section later in this report.
[22] Autran uses a longitudinal drive shaft, U-joints, and differentials to transmit power from one motor to all four wheels.
[23] Auxiliary wheels would be engaged to provide more traction when necessary to climb grades of 10% or more.
[24] Frog offers a hybrid or combustion engine as an optional alternative to a battery. Batteries are recharged using an arm which extends to make contact with a power supply. Alternately, batteries can be physically swapped out depending on the application.
[25] 10% grade results in reduced acceleration capability. Frog did not supply a specific grade-climbing limit.
[26] Higherway specifies liquid cooled permanent magnet brushless DC motors. Aluminum/stainless steel powerbar carries 600 -750 VDC with 360 Hz AC ripple. Sliders transfer power to vehicle and to power return through track.
[27] 20%, but not for unlimited time at design arterial speed (45 m/s). Some weather conditions will limit the maximum grade due to loss of traction or limit maximum time or speed due to motor wheel overheating. The 20 % maximum is only possible because the bogie design has all wheel drive and idler wheels to increase the force on the track to greater than the vehicle weight. The idler wheels are only engaged when increased traction is needed.
[28] MAIT does not specify the drive system, only the container handling system.
[29] MegaRail and MicroRail also use battery backup power.
[30] Grade for MegaRail and MicroRail can be increased to 15% at lower speeds.

SwedeTrack	? VAC motor, 600 VDC supply	contact plus battery	4/4	?	?
ULTra	? DC	battery – opportunity recharging	1/2	rubber/?	?
Urbanaut[34]	750 VAC	?	4/4 ?	rubber/concrete	12

Mitchell

In the Mitchell system, electric motors are mounted in the guideway. Each motor drives one rubber wheel, which pushes the vehicle to the next wheel. Wheels are apparently spaced at approximately one vehicle-length. The system forces all vehicles to travel the same speed and enforces a constant headway time (not distance). Mitchell claims that the system reduces the cost of the control system.. Failure of a motor, or even up to 8 motors in a row, will not disable the system because the vehicles can coast through failed regions and be re-accelerated by the next functioning motor.

The vehicle runs on rubber wheels on a steel running surface. The maximum grade is 10%

Power is supplied to the vehicle for passenger amenities only. See the section above "Evaluation of electric passenger amenities."

Taxi 2000

In the Taxi 2000 system, the drive is a pair of linear induction motors (LIMs) mounted in parallel on the vehicle. See footnote for definition of LIM and LSM.[35] They operate against the horizontal running surface on a special bogie that permits a very small air gap.

Power is transferred to the vehicle via contact with a 600 VDC power rail, and it is then converted on board to variable-frequency, variable-voltage AC. (The frequency increases with speed, optimized so that current is minimized.)

Tires are rubber. Maximum grade is 10%, but could be increased with larger motors if the terrain made it necessary.

Regarding the tradeoff between on-board vs. wayside LIMs, Taxi 2000 found that having the LIMs on board minimizes the system cost even down to half-second headway.

Taxi 2000 is watching the development of linear synchronous motors (LSMs) and would go to them if they result in lower cost per passenger-mile, but currently they do not.

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[31] According to Ruf, "The maxi-ruf can be used in a mixed mode. Partly train powered from the guideway and partly tram running on battery power. This way, a tram line can be made without rails in the road surface and without overhead wires. Establishing costs are extremely low and the line can easily be redirected if needed. The trick is to run the maxi-ruf as a train most of the time (charging batteries from the rail) and then crossing the dense parts of town as a battery driven tram before again entering the rail. This "pendulum tram" solution has all the good qualities of a tram without having the problems."

[32] Power supply is DC.

[33] On the track, steel wheel run on rubber rails; on the road surface, standard rubber auto tires are used.

[34] Urbanaut suggests that the system could be built with LIMs instead of in-wheel motors.

[35] A rotary motor works by the magnetic force between a permanent magnet and an electromagnet. The electromagnets are mounted in a fixed circular configuration while the permanent magnet rotates within the circle, or vice versa. A linear motor is like a rotary motor that has been unwound and laid flat. The vehicle is the permanent magnet, and the electromagnetic windings are mounted linearly on the guideway, or vice versa. For greatest efficiency, the gap between the two should be as small as possible. In a linear synchronous motor (LSM) applied to PRT, the motor frequency is changed continuously to match the vehicle speed, and the vehicle rides the magnetic wave synchronously like a surfer riding an ocean wave. In a linear induction motor (LIM) applied to PRT, the vehicle speed does not necessarily match the motor speed. In either case, the amount of power applied to the motor controls vehicle acceleration, as with any electric motor.

- Grade-climbing – Among systems where grade-climbing ability is reported, all meet the suggested minimum of 10%.
- Support for reliability claims – Autran, Frog,[36] and ULTra are the systems that only have one motor in a vehicle. Those systems with more than one motor may be less susceptible to a motor failure.
- All-weather traction – Several systems raised concerns for the committee about all-weather traction. Systems having rail surfaces exposed to the weather would have reduced traction when ice was present. This would influence the safe following distance (which impacts capacity), and could limit grade-climbing ability. These systems are: Austrans, CyberTran, Frog,[37] Ruf, ULTra, and Urbanaut. The other systems have protected traction surfaces, or do not use traction for propulsion. However, Ruf and Austrans feature variable-pressure systems to increase traction when needed.
- Battery recharge time – Frog, Mitchell, Pathfinder, and ULTra use batteries which are recharged in stations. In order to add credibility to these systems, vendors should demonstrate with a simulation model that the available recharge time is sufficient to keep up with demand. If a vehicle stopped in a station only has 30 seconds of time available for charging before the berth is needed for the next vehicle, this seems insufficient for battery technologies that we know of. In addition, Mitchell recharges batteries in stations, but only for cabin load, not for propulsion. If battery-swapping is to be used as the normal method to keep these vehicles in service for long intervals, the swapping system would have to operate automatically with adequate reliability.

Vendor notes on propulsion and traction

- Autran - Auxiliary wheels which control direction and switching are also controllable to obtain increased traction when necessary on inclines or for acceleration and braking.
- Ruf - In icy surroundings, the RUF system has a special feature which prevents problems. The drive wheels run on a surface of hard rubber so that if ice covers the surface, the drive wheels will make the ice break because of the deformation of the rubber surface.
- Ruf - Adjustable friction between the top of the rail and the drive wheels makes it possible to negotiate steep grades (20%) and still have low friction when desired. This is possible because of the special configuration of the drive wheels which can be pressed against both sides of the rail. This way, the friction can be dynamically adjusted to the optimal size.

[36] According to Frog, "The reliability of the system is increased by using only one propulsion motor. This might seem contradictory, but our two pilot project proved that minimizing complexity is favourable towards reliability." Other developers appear to disagree with this assertion.
[37] Frog intends to vary vehicle operations, such as acceleration, according to the weather.

Switching and steering

How switching relates to other factors

The customer requirements that switching relates to are primarily capacity and safety. The biggest issues surrounding switch design are (1) that is should cycle fast enough from one side to the other, to permit close vehicle spacing, and (2) that the vehicle could never be caught in a half-activated switch and strike the diverge point head on, failing to choose right or left.

Switching is so central to PRT, that we treat it in a separate section in this report. However, there are no direct customer requirements around switching, as the customer should only care about the capacity and safety that result from the overall design, and not the switch design itself.

Description of switching systems

There are two classes of switches. In guideway-based switching, the guideway physically moves, similar to train and monorail and almost all other transit systems ever built. In vehicle-based switching, the guideway has no moving parts, and the vehicle moves a wheel or other device to cause it to either follow the left track or the right track.

Most of the systems use vehicle-based switching. One system uses a combination of the two.

Vehicle-based switch

- Autran – Switching is performed by shifting control wheels of a vehicle on one side to allow control wheels on the opposite side to control the direction.
- Frog – System runs on a flat road surface. Steering is automated by counting wheel revolutions to measure the distance traveled and the steering angle to determine the direction, while verifying the calculated position by use of reference points in the road (magnets). The software can work independent of the passive reference points, but these are used to increase the accuracy of driving. The virtual guideway shape (the map) is defined at the central control tier and sent to the vehicle, and the vehicle executes the steering maneuvers based on this map data.
- Higherway – Steering is computer-controlled electromechanical with optical input and mechanical backup. The switch consists of pairs of stabilizer wheels linked together and switched by electromagnets (solenoids). The stabilizer wheels engage guides in the Y-sections (where the

track diverges or merges) of track to pull the vehicle to the right or left and keep the motor wheels from falling through the gap in the track.

- MegaRail and MicroRail – Vehicles are steered to follow either the right or left side power rails. Switching is accomplished by vehicles shifting steering references between left and right side power rails. Steering shifts are accomplished before Y points are reached in order to allow complete safety checks of the steering prior to vehicles reaching the switch Y points.
- Pathfinder – Switch wheel interacts with guideway at junctions to initiate turning movement.
- Ruf – Switching uses the dual mode principle combined with magnetic guidance. In the switch area the speed is reduced to 30 kph and the vehicles use their road wheels. The triangular guideway disappears so the vehicles can move freely on the road surface. The guidance system uses magnetic fields at different frequencies from two parallel wires just below the road surface. The frequencies are in the range from 8 to 15 kHz. This way one switch can guide the vehicles in several different directions. There is no delay since there are no moving parts. A multi directional switch takes up far less space than an ordinary PRT switch with the same number of switch directions.
- Taxi 2000 – Vehicles are guided laterally by means of 4 polyurethane tired wheels near the top of the chassis to give yaw stability and 2 polyurethane tired wheels near the bottom of the chassis to add roll stability. (4 wheels near the bottom would warp the chassis in the spiral sections into superelevated turns.) Switching is by means of a pair of vehicle-borne switch arms slaved together that rotate about a longitudinal axis and have polyurethane tired wheels at each end that grab a rail mounted in the branching sections of the guideway. The arm is designed so that the line of force from the wheel passes through the center of the bearing, which makes the switch self-centering. A spring makes the switch bi-stable.
- ULTra – Electronic guidance with curbs for safety retention. In vehicle Ackermann type steering.

<u>Guideway-based switch</u>

- Austrans - Vehicle is rail guided using cylindrical wheels (not the conical wheels more normally seen on rail vehicles) and in-track switching (functionally similar to regular rail).

<u>Vehicle-activated guideway switch</u>

- Cybertran – Vehicle is rail guided using coned wheels on a single rigid axle, like conventional trains, and in-track switching. While the switch is similar to a conventional rail switch, it is activated by the vehicle itself.
- SwedeTrack – The switch mechanism is unclear to us. The vehicle can steer the front and rear bogies to 10 degrees to roll smoothly in curves.

<u>Other switch types</u>

- MAIT does not specify a switch, only the container handling system.
- Mitchell – Offers a switch that is normally vehicle activated but can be overridden by the guideway. The in-vehicle switch is an electromechanical device activated by the passenger's station selection or pushing of an "exit" button. The activation will control two types of pins on the car. When one is extended the other is retracted. One pin is concentric with pivot axle of the tow bar at the front of the car. The other type of pin is a turning pin. It is located off-center near the front wheels. At each diverge switch there is a deck. The deck has two sets of slots, straight and turning. During mainline travel the center pin remains extended, the car will follow the center slot on the deck and continue straight. When the switch is activated the turning pins are extended (the center pin will inversely retract) and the car will follow the turn slots in the deck. Under abnormal conditions there are two "over-ride" safety vanes under the deck that can be positively positioned by station or central control. The systems can switch the side vane so that no car can

turn. The vane under the center slot can also be switched by the system so that all cars are forced into the turn. These safety features can be utilized in the event of a power failure, system emergency, or to direct a vehicle to a police station.

- Urbanaut – Offers three types of switches. The in-vehicle switch (details not available) would be used in stations at slow speed. The usual line-speed switch would involve bending the metal guidance fin. A third option is a swivel switch, which would apply when two tracks cross at grade.

Evaluation of switching systems

The committee sides with the majority of developers in the thinking that a vehicle-based switch is an improved design over a conventional rail switch. Its advantage with regard to vehicle spacing is that two or more vehicles can be in the diverge area of a switch at the same time and be going different directions. If any moving parts are used in the guideway, the leading vehicle has to completely traverse the diverge section, and then time must elapse for the switch action, plus enough time for switch verification and an emergency stop should the switch or sensor fail, prior to the next vehicle entering the diverge section.

Within the group of vehicle-based switched designs, some may be safer than others. Ideally a passive mechanical design feature would prevent crashing into the diverge point. We didn't get enough detailed information to be able to judge the safety of these designs, but three systems may have issues related to this:

- Frog relies entirely on electronic guidance, and has no passive safety steering feature (because it is designed for flat road use).
- ULTra similarly uses rubber tired car-like vehicles, and appears to lack a passive safety steering feature.
- Ruf uses road-tires only in switches, where it relies on electronic guidance, and therefore could have the same problem. "A passive system for safe guidance onto the rail has been designed but not yet published", according to Ruf.

Finally, it is noted that headways for Cybertran and Urbanaut are large compared to other designs, and part of this headway requirement may be related to the switching speed. For Cybertran, guideway based switch is activated by the vehicle, and for Urbanaut, part of the guideway bends.

Control, reliability, capacity, related information

Explanation of related design factors

This section encompasses a variety of related topics. The topics are bunched together because they impact each other and cannot be reasonably assessed individually. These are as follows:

Speed

Speed is often overrated and overestimated by car-drivers. Actual average driving speeds are usually between 10 and 40 kph in urban areas (6-24 mph), even though top speeds are much higher. Urban driving is characterized by repeated rapid acceleration and frequent complete stops. Since PRT is designed so that all vehicles travel at nearly the same speed at all times all over the network, with no stops, a system that only traveled at 30-50 kph (19-31 mph) would actually be competitive with driving a car. However, much faster systems are proposed.

Factors that are related to speed are:

- Aerodynamic – More energy is used for a given trip length, if the travel is faster.[38]
- Curvature – Tight curves require slowing down; this is a factor of the installation site, not the technology. However, banked turns can partially alleviate the speed penalty in curves.
- Length of on-ramps/off-ramps – In order to accelerate from a station to a faster line speed, a longer and more expensive on-ramp is needed.
- Headway – see next

Headway (separation)

Headway is the spacing from one vehicle to the next. It is sometimes expressed in time (e.g. 2 s headway), and sometimes in distance (e.g. 5 m headway). Sometimes it is measured from the head of one

[38] Note that there are also aspects of consumption per unit distance which increase with low speeds such as auxiliary vehicle and system power requirements and slower systems requiring more vehicles.

vehicle to the head of the next (for capacity calculations), and sometimes from the tail of one vehicle to the head of the next (for safe stopping distance calculations).

Trains have headways measured in minutes, while cars and PRT have headways measured in seconds. The difference is due to two main things; first, the fact that trains can only decelerate gradually, while cars and PRT are generally designed to decelerate abruptly in emergencies. Short PRT headways like 1-2 s may seem absurd for those who are accustomed to train headways, but it is actually reasonable because the technology is entirely different and designed with that in mind. Second, trains are designed to stop on-line, while PRT is designed to stop off-line.

Safe stopping distance is the distance that is required between vehicles, such that if the leading vehicle stops unexpectedly, the following vehicle can stop safely without colliding. In rudimentary theory, safe stopping distance increases proportionally to the square of the speed. The time between vehicles traveling at a safe stopping distance increases proportionally to the speed. Therefore the higher the design speed, the lower the capacity, other factors being equal.

Car drivers typically exhibit the unconscious behavior of increasing their following distance proportionally to the square of their speed at speeds over 50 kph, confirming the basic theory. In the case of highways, the load is an independent variable: the number of cars entering the highway is uncontrollable.[39] The speed of the resulting traffic flow depends on the load: the more cars, the slower they go. (Converse: the faster a highway is flowing, the lower its throughput.[40])

With PRT, however, load is a controlled variable, so that congestion does not occur. If the demand for the system is more than the capacity (at the optimal speeds) then the riders must wait at the origin until there is room. Then, once there is room, the trip proceeds without delays.

Some systems propose constant-time headways regardless of speed, such that the line capacity is constant and speed is only affected by geometric factors. In these systems, the safe stopping headway time must be calculated at the maximum speed, and that headway then used at all speeds. Other systems may allow increased loads in lower-speed sections, and/or vary the speed somewhat depending on the demand (like highways).

Safe stopping distance is not necessarily a requirement between *every* vehicle. There are two kinds of emergency stops: brick-wall, or sudden stops, and gradual stops. Brick-wall stops would occur if a tree or other large object fell on the guideway. Gradual stops would occur under most classes of vehicle or communications malfunction. If a vendor can show that brick-wall stops are very unlikely, and that collisions caused by brick-wall stops are not fatal, then the risks of a system that operates below safe stopping distance (for brick-wall stops) is a justifiable risk to take. We propose customer-oriented requirements on this topic in the safety section of this study.

Major factors that are related to headway are:

- traction and braking – Steel on steel is a low friction technology that is unsuitable for emergency deceleration. A PRT system must have high-traction wheels (if vehicle propulsion is used), or emergency braking by some other means, such as brake pads gripping the guideway or linear-motor braking.
- control system – The reliability of the control system, including the speed of communications, affects safe headways, because in an emergency or non-emergency deceleration, the system must detect the deceleration and the following vehicle must receive and respond to the command to slow down.
- merge and diverge points, and switch cycle time – If a guideway-based switch is used, the switch cycle time affects safe headways. The switch activation time must be added to the safe headway

[39] There are driver information systems and access control systems that address this issue in some areas.
[40] The text is relevant for PRT and highways at higher speeds. On highways, flow is very roughly a negative parabola – maximum throughput occurs at some speed – generally in the region of 40mph – and at lower speeds, the throughput also goes down.

time between each vehicle. If adjacent vehicles to go separate directions in a switch, the following vehicle must remain at least at a safe stopping distance from the switch during the activation time of the switch. This extra separation can be partially mitigated if adjacent vehicles are to be routed in the same direction.

- capacity – Minimum headway is directly related to capacity as noted above.

Capacity

When studying PRT, capacity should refer to vehicles, not passengers. Vehicle sizes are listed in another section, but the vehicle loading is likely to be the same for any system running in PRT mode, regardless of vehicle size. For the purposes of this report, we are assuming that the systems billed as PRT, as well as those systems with larger vehicles (such as Austrans and Cybertran) will all be running in PRT mode, that is, serving only one passenger at a time or a group wishing to travel together.

Note the difference between two types of capacity:

- Line capacity – generally measured as the number of vehicles passing a point on the guideway per hour (e.g. 2,000 vehicles/hr).
- Network capacity – the number of passengers that can be served in a PRT network per hour or per day. Or, this can also mean the average of all line capacities for a given network.

Calculations of network capacity are not done in this study because they depend on the specific network and city. Line capacity numbers will be avoided so as not to give the false impression that line capacity equals the number of passengers served. This has often been incorrectly assumed by those familiar with planning for mass transit. Instead we will list vehicle separations, in seconds.

Capacity isn't the issue directly, when choosing a transportation solution. Higher capacity isn't necessarily better. The issue with regard to quantity of service is: how much does it cost (how many guideways and stations) to serve the actual ridership demand? The vehicle separation (corresponding to line capacity) is one input into a model that can predict the answer.

Location detection

The control system must know where the vehicles are. Counting wheel rotations and using GPS (global positioning system) and guideway optical or magnetic markings are possible ways of doing this.

Control system configuration

The control systems of the systems studied generally have multiple levels: vehicle, guideway, and central. (Or a subset of the three.) Control in this report encompasses:

- A set of computers that automate the network operation. Computers may be located on board the vehicle, in each guideway segment, and/or in central locations.
- Communication between the levels of control systems; and between vehicles; and between guideway segments; and between regional control centers. (radio, fiber optic, etc.)
- Command strategy – which component makes decisions about acceleration, switching, door opening, etc.

Since a control system is such a large and technically detailed project, it is far beyond the scope of this study to evaluate control algorithms. However, an easier first level of proof of concept is the existence of a simulated control system. That is, if a vendor can demonstrate their control algorithms in a visual simulation, this can be a proof of concept of the control algorithms. Seeing a simulation, however, does not mean that the developer has solved the control problems.

Reliability

Reliability is another large area of concern for a potential buyer, but again the details are beyond what can be done in this report. Major reliability factors are:

- durability of the components (vehicles, motors, etc.)
- component redundancy (for example, having two separate motors) and other detail design choices affecting reliability
- modularity – ability to swap out components with replacements
- observed reliability in test operations
- dependence on the electricity grid, vs. battery backup

Note that a large PRT network is inherently redundant even if the components within the vehicles and guideway are not redundant. The fact that multiple routes can serve the same trip, and that multiple vehicles are available makes the system more reliable than mass transit. However, initial systems will probably be small and will not have this type of redundancy.

Evaluation criteria

- Speed is at least 30 kph, so that trips across a city are comprable to an automobile in duration.
- System uses fully automated driving and routing using fail-safe control system.
- System does not rely on a single centralized control system for operation. Any or all central control can be severed without disabling the system.
- Simulation of control system is available to plan site-specific network.
- Inoperational vehicles do not disable the whole system, and can be removed from the guideway without demolition.
- A disabled part of the network allows continued operation around the affected area.
- Vehicles and guideway segments can be swapped out with new replacements.
- System should meet numerical reliability and availability standards, similar to those set for other transit.
- System allows close vehicle separation of about 3 s or less, with a separation of 1 s or less preferred.[41]
- Rerouting on account of a disabled component is instantaneous.

Evaluation of separation and speed

The following table lists the separation and speeds planned for each system.

System	Min. Vehicle separation (nose to nose)	Min. Vehicle separation (tail to nose)	At speed (kph)	Design speed(s) / Max speed (kph)
Austrans			120	120 / 120
Autran	1.0 s	2.0 m	135	135 / 160

[41] A separation of more than 2-4 s may not economical for true PRT operation. We don't feel it is necessary to state an absolute requirement in this area because the economics of it will drive the developers to achieve the shortest separations possible. The buyer should ultimately compare systems based on passengers served, not track distance, so the vehicle separation will be a big factor in the price per unit of service.

System	Min. Vehicle separation (nose to nose)	Min. Vehicle separation (tail to nose)	At speed (kph)	Design speed(s) / Max speed (kph)
Cybertran	15 s [42]		96	see note[43]
Frog	5 s		40	40 / 100+
Higherway	0.5 s	0.4 s	162	162 / unknown
MegaRail	16 m (~0.3 s) [44]		200	50,112,200 / 200
MicroRail	16 m (~0.3 s)		104	50,104 / 104
Mitchell		0.045 s (~0.3 m) [45]	50	24-160 / 480
Pathfinder	2.0 s			32 / 50+
Ruf	1.0 s[46]		30	120 / 150 [47]
SwedeTrack	0.5 s ?			145 / 145
Taxi 2000	0.5 s	0.25 - 0.5 s	65	32 / 65+
ULTra				40 / 40
Urbanaut	5.0 s		65	65 / 65

There is great variability here in design approaches. Speeds range from 32-50 kph on the low end of design speed, to 150-200 on the upper end of maximum speed, with one extreme case, Mitchell, claiming a theoretical maximum of 480.

The way a company defines "design speed" versus "maximum speed" is not necessarily consistent, so for the evaluation, we will assume that the system can operate from zero up to the stated maximum speed. The only system whose max speed is below the 50 kph suggested requirement is ULTra at 40 kph.

Most systems claim to be able to go over 100 kph, and there is no reason to doubt this, since many trains and light rail and other systems in operation achieve this speed.

Vehicle separations are mostly in the range 0.5 –2.0 s, with two systems at 5 s. CyberTran is much higher, and would therefore have very low capacity in PRT service mode. ULTra and Austrans are not reported.

On the low end, Higherway, MegaRail, MicroRail, Mitchell, and Ruf claim sub-second separations. These systems rely on physical traction to maintain safety at the close spacing. Only Mitchell has actually tested close spacings, but we don't know with what safety criteria. Other vendors have noted that separations may decrease with further research. In their favor, all of the sub-second systems have

[42] Cybertran proposes to lower speeds in order to decrease separation and increase line capacity in peak periods as needed.

[43] CyberTran is designed for 3 different markets, with low speed markets (airports, parks, business complexes, etc) of up to 50 kph, medium speed markets (commuter corridors, LRT type systems, connectors to conventional transit systems) of up to 128 kph, and high speed markets (intercity corridors) up to 240 kph.

[44] MegaRail and MicroRail propose separation based on constant distance regardless of speed; therefore their capacity goes up with speed. According to the company, "As all vehicles are moving at a constant speed and have the same basic physical characteristics, it is not physically possible for a vehicle to come to an abrupt stop. If any vehicle drops from the constant speed, all following vehicles are commanded to precisely match the deceleration of that vehicle. Hence typical safe stopping distance considerations do not apply."

[45] Mitchell has an interesting way to increase capacity at higher speeds. First two separate parallel lines are accelerated so that the vehicle spacing increases while the throughput remains the same. Then the vehicles on the two lines are interleaved together on a single high speed line. The high speed line would then have to be split in two before deceleration occurs on the other end. We note a concern about emergency stopping in this situation.

[46] Ruf also supports platooning. Vehicles in a platoon are only separated by 0.1 m at 150 kph. Platoons are separated from other platoons by 10 m at 30 kph, or 185 m at 150 kph.

[47] In a switch, Ruf must slow down to 30 kph.

weather-protected traction surfaces except Ruf. We think Ruf would need to further justify the claim of 0.1 m spacing when ice is present.

Taxi 2000, at 0.5 s spacing, does not depend on physical traction, since the linear induction motor accelerates and decelerates the vehicle.

Evaluation of control and related factors

To reiterate the customer requirements of a control system, it must (1) safely react to failures, (2) not rely on a central control tier, and (3) isolate and continue to operate around disabled areas.

It is far beyond the scope of this study to evaluate whether the proposed systems will meet these requirements. It is noted that the control strategies are remarkably similar, and that on the surface, there are no apparent problems with any of the approaches.

Development of the control system is an expensive item that has not been completed by most vendors (see section on Development Status)

Description of control strategy

- Cybertran - CyberTran uses a 3 tier system with monitoring, control, and data transmission in a central control unit, distributed along the guideway, and in each vehicle. Communication between the individual tiers is a combination of radio, Ethernet, and fiber optic cables.
- Frog – Two-tier system, in which the self-guiding vehicles communicate with a central controller dubbed SuperFROG. Communication is by radio. In the simplest applications, SuperFROG can be a single Linux PC. Frog relies on an infrared obstacle detection system.
- Higherway - Three tiers - 1) Main routing and billing, 2) local traffic management, 3)vehicle. Fiber optic communications between tiers 1 and 2. Radio and infrared communications between vehicles and local traffic management. Fiber optics plus radio and infrared between main routing and billing and vehicles. Passengers will interact with the control system through radio frequency identification readers and telephones. Vehicles communicate to passengers with speakers and displays. System operators interact through keyboards, mice and voice recognition. (Design is not complete and inventor expects to team with some organization with more control system competence.)
- MegaRail and MicroRail - Multi-level, hierarchical control structure with the number of layers dependent upon system overall size. First layer is in vehicle, second layer is in guideway section, and supervisory layers connect to section layers. Guideway layers communicate directly with adjacent guideway sections. Individual vehicles also communicate directly with adjacent vehicles.
- Mitchell – Three levels of control, Master Control, Station Controls, and Vehicle control. Most command and control functions are designed into the hardware. Mitchell advertises a much less complex and less costly control system than other systems due to guideway-based propulsion.
- Ruf - 3-tier system with central, junction, and vehicle. Central control performs dynamic route allocation and makes sure that no segment is overloaded. Guideway has a fixed speed profile but with adjustable top speed. Junction control performs merging of all incoming vehicles via leaky coaxial cable in guideway. Guideway top speed can be controlled. Vehicle control communicates with all vehicles in train and with the junction control. Vehicle also communicates with passengers and with the Internet.
- Taxi 2000 – information not supplied

Vendor notes on control strategies

- Higherway - Each section of track will have a GPS-compatible location code attached at the factory. The vehicles will have sensors to read these codes. The vehicle computers will have system maps stored in them so that the vehicles will be able to find their way to their destination even if the communication links to the other system computers are lost. The combination of track location codes and dead reckoning from the motor wheel controller data will enable the vehicle computers to know their location to the required accuracy for navigation. Obstacle sensors will detect tree branches and pedestrians and the vehicle. Vehicle will brake if necessary to avoid hitting them when possible.
- SwedeTrack - Uses cooperating regional computers, beam node computers, drive wagon computers, and a lot of smaller computers in switches, brakes, lifts, cabins, seats etc. All calculations of significance to traffic safety are made in three independent computers. All communications between computers of significance to traffic safety are tripled: Fiber cables on top of the beam, microwave conductors and a cell radio channel inside the beam, and high capacity information cables inside the vehicle. The coherence of the three computer resulting messages is controlled.

Environmental, energy

Energy use in PRT

All systems propose all-electric operation. Electric power is used primarily for propulsion and vehicle amenities. Following is a description of the ultimate use of the power. This is just background theory, and is not indicative of energy performance of any particular system.

1. Some power is lost in transmission from the source to the motor.
2. Of the power that reaches the motor, some is lost in the motor's inefficiency, and the remainder provides motive force.
3. Of that motive power, some is lost in rolling resistance, some lost in aerodynamic drag, some in vibrations (shock absorption), and the remainder provides for acceleration (increasing kinetic energy).
4. Of the kinetic energy stored in the moving vehicle, some may be regained with regenerative braking and the remainder is lost in friction braking.

A measure of the power required to move at a certain constant speed is the low-limit of the actual power demand prediction. A more realistic number is the total energy required to accelerate from still to a certain speed, travel a certain distance, and stop again.

Also note that as with any transit system, some power is used to move around empty seats. With PRT, empty vehicles are sometimes routed to another station where there is a higher demand.

Evaluation criteria

- Energy use less than average car with single occupant (SOV)
- Noise level lower than mass transit. 75 dBA at 5 m at 50 kph would be acceptable. (Cars and trains can produce 70-90 dBA)
- Use of the system will improve air quality, as demonstrated by a simulation model showing substantial capture of prior auto traffic.
- No vehicle air emissions.
- Hazardous materials not used in production.

- Propulsion energy waste minimized through such techniques as aerodynamic shape, regenerative braking, efficient motors, and minimal rolling resistance.
- Cabin energy waste minimized through efficient lighting and passive/marginal climate control, insulation, etc.

Evaluation of external noise

Systems that have been able to measure the actual noise generated by a prototype are as follows:

System	Noise level (dBA), at speed and distance	Justification
Austrans	77 dBA at ? m, ? kph	prototype measurement
Frog	65 dBA at 7.7 m, 35 kph	prototype measurement
Cabintaxi[48]	43 dBA at 7.5 m, ? kph	prototype measurement
SwedeTrack	55 dBA at ? m, 72 kph	?
ULTra	42 dBA at 2.5 m, ? kph	?

It appears that noise will not be a problem for any system, based on a few estimates and a knowledge of the technology compared to other vehicle types. Basically, electric motors, light vehicles, and smooth running surfaces are a feature of every system, and these ingredients are a good recipe for a quiet system.

Noise abatement notes from vendors

- Autran - The noise level is expected to be very low, less than that produced by wheels with tires. Steel wheels are used but will not produce the noises normally associated with designs like those used in conventional trains. Tracks and track supports are designed to provide a very smooth path of travel. In addition, generation of noise during turning is minimized. The design is unlike that of bogies of conventional trains and of at least some proposed PRT vehicles that use two pairs of wheels on axes in fixed parallel relation and that generate noise when overcoming large frictional forces that are developed when changing direction of travel. In Autran vehicles, front and rear bogies are used, each having two wheels driven through a differential. To change direction, the bogies turn about vertical axes, avoiding the aforementioned large frictional forces and associated noise, also allowing turns of very short radius.
- Cybertran - We have not yet tested the vehicle for noise levels, but have designed a number of sound abatement components and concepts into the system. These include hollow wheels filled with sound absorbing material, rails mounted on elastic, sound absorbing material, vibration and shock isolation of the vehicle body from the propulsion units, and sound deadening materials within the vehicle itself.
- MegaRail and MicroRail - Cars operate on rubber tires on smooth steel traction rails in steel rail boxes that are enclosed except for inverted five-inch wide slots on the inside sides of the rail boxes. Most of the noise produced by the tire operation is contained within the rail boxes.

Evaluation of energy usage

This table shows the power requirements for moving a single vehicle, for those systems where the value is known. The rows of the table cannot be directly compared because power levels are listed for different speeds and different sized vehicles.

[48] Data reported by Taxi 2000

System	At speed (kph)	Power (kW) for constant motion at 0% grade	Motor sizing (kW) x number of motors
Austrans	?	39	?
Autran	100	7 (up to 55 for large vehicles)	25 x 1 [49]
Cybertran	100	10	30 x 2 75 x 2 75 x 2
Frog	40	13.5	20 x 1
Higherway/Dove	161	5 – estimate	25 x 2
Higherway/Pelican	161	10 – estimate	50 x 2
MegaRail		unknown	unknown
MicroRail		unknown	unknown
Mitchell	24 48	1.5 3.5 [50]	various
Pathfinder			
Ruf		various[51]	10 x 2
SwedeTrack		unknown	
Taxi 2000	25	4 [52]	2 linear motors
ULTra	?	2	
Urbanaut	65		37 x 2

From this we see that 4-10 kW is expected for most systems, while ULTra claims only 2 kW (4-passenger battery-powered vehicle) and Austrans specifies a much larger 39 kW (9-passenger vehicle).

The use of GRT-sized cars to provide PRT service, in which one passenger was carried by a 6+ passenger vehicle, could result in unnecessary energy waste, and could even use more energy in total than cars.

Conversion from Power to Energy Usage

Assumptions

Average new passenger vehicle efficiency in 2001 was 20.4mpg (note – fleet average is slightly higher as new vehicle efficiencies tend to be lower than retired vehicles).

Average energy content of gasoline is 132MJ/gal (high rating, typical for power plants)

Average power conversion efficiency: 33%

So a power plant generates approximately 12.1kWh / US gal. Thus a vehicle requires approximately 593Wh/mi or 370Wh/km equivalent.

Application to vendor-reported values

Estimates for PRT energy consumption have a fairly broad range. All systems plan to operate electrically, eliminating vehicular air pollution. Vehicles are generally expected to exceed current passenger vehicle efficiency levels, although some larger vehicles have significant energy requirements.

[49] Up to 100 kW motors would be used for various applications (e.g. pallets, freight).
[50] In the Mitchell system, motors are turned off when not in use. The power requirements are based on actual test track measurements. Mainline motors were switch activated and never started under load.
[51] Various vehicle designs have different weights and therefore different power requirements.
[52] Includes yearly average heating and air conditioning.

A current passenger vehicle (2001, mix of all passenger vehicle types) achieves on average 20.4 miles per U.S. gallon. At current typical power plant efficiency levels (33%), that is equivalent to 370Wh/km. By comparison, here are some expected values for various PRT systems (lower numbers are better):

- Austrans – 39kW @ 100km/h = 390Wh/km
- Cybertran – 10kW @ 100km/h = 100Wh/km
- Frog – 13.5kW @ 40km/h = 338Wh/km
- Higherway – 5kW @ 161km/h = 31Wh/km & 10kW = 62Wh/km
- Mitchell – 1.5kW @ 24 = 62.5Wh/km, 3.5 @ 48=73Wh/km
- Taxi2K – 4 @ 25 = 160Wh/km

There is quite a wide variation in expected consumption levels (over a factor of 10), partly due to wide variation in vehicle sizes, and may also reflect the extent to which these numbers are still estimates. In the case of Frog, data is assumed to be from actual operation. Note that in PRT operation, total consumption would need to include energy consumed by empty vehicles (expected to be around 1/3 of total distance), vehicle accessories (and, in some cases, battery losses), and transit facilities, although automotive traffic has similar requirements (e.g. trips to pick-up passengers and energy used for road safety / traffic management) making detailed comparisons very difficult, particularly at this early stage. However, most systems expect to achieve significant improvements in energy efficiency.

Other environmental evaluations

Other environmental evaluations (hazardous materials, cabin energy efficiency, regenerative braking) are not evaluated for the same reason as above; displacement of cars will be a net benefit in all of these areas.

Safety

Discussion

<u>How to formulate safety requirements</u>

There is little doubt that any PRT system would be far safer than cars, and we won't repeat the arguments here. (See the introduction to this report or many of the vendors' web sites.) However, the question remains of what safety level to design for. It is very important to avoid importing safety criteria from other forms of transportation, because the failure mode analysis is different.

In the opinion of the committee, the public safety standards should be expressed in terms of the number of allowable deaths and injuries per million-km traveled. Ideally of course, the goal is zero injuries. However, setting the bar too high would prevent the system from operating. The more lenient the safety requirements, the quicker a PRT deployment could be made (and/or it could serve more passengers), and the more lives would be saved by diverting passengers away from cars. We think that a reasonable standard for PRT is to set the accident rate anywhere in the range of 2 to 10 times lower than the current accident rate for cars, which would still be quite lenient. Setting it in this manner would be a strategic way to protect the overall safety of the public. In the distant future, if PRT does capture a large share of travelers, then the safety standards should be improved at that time.

It is tempting to form requirements that depend on the technology, such as specifying a minimum of 0.5 g deceleration, or isolating vehicles so that a derailment of one vehicle cannot affect another one, or specifying airbags, etc. We believe all of these kinds of requirements are inappropriate because the task of proving that the system is safe, and deciding which devices and strategies to use to meet the requirements, should be up to the vendor, not the customer or the public.

As an example, a hypothetical system could take the approach of using low speeds and passenger protection, while designing to allow occasional bumps. In this example, suppose the system was designed and monitored to stay at or below one collision per 1,000 km traveled – a very high level. The system would operate at 30 kph and require that passengers wear seat belts, and use springed bumpers. The end result of this system is that safety is ensured, because collisions, although relatively common, are very unlikely to result in injury. While no one should be *required* to purchase or use this system, it should be *permitted* by the public to operate.

A different hypothetical system may use entirely different devices to ensure safety. These could include operating at larger vehicle separations, using a sophisticated control system, using seating that faces to the rear, etc. The point is that the devices chosen by the vendor should be allowable devices, as long as the end result of safety can be proven, and that proof can be verified by independent engineers.

Some safety devices are in nuances of the control strategy rather than in hardware. For example, a strategy that allows for very high capacity but reduces the *number* of vehicles involved in a potential collision is the use of platoons of about 10 vehicles. Vehicles in a platoon can be spaced with almost no gaps. Larger gaps would be used between platoons. A mechanical failure would only affect the following vehicles within the platoon, but not the next platoon. While this particular example was not mentioned by any vendor, it demonstrates how complex and creative strategies can be used to achieve public goals. If the publicly defined requirement included a specific vehicle separation, then this strategy would be ruled out. When the public starts defining specific technological strategies, it could block entrepreneurial creativity and be counterproductive to public goals.

How safety would be demonstrated

Because safety could not reasonably be demonstrated with a small test system, it would have to be demonstrated in revenue operation. The catch is, of course, that a revenue system would not be permitted until safety standards were demonstrated. There is a way out of this catch, however. A system operator wishing to install a new system can start out with longer headways or other control system measures until enough data accumulated to prove the reliability, then shorten the headways and increase capacity later. This approach would meet public safety the requirement while allowing testing in revenue operations.

In addition to this approach of demonstrating actual safety statistics, an independent engineering firm would have to validate the safety methodology of the system vendor.

Issues with emergency egress

It is tempting to require emergency egress walkways and ladders from all points on the guideway, as this is a simple way of ensuring safety under failure conditions. However, there are reasons why other ways of ensuring safety under failure conditions could be more sensible and cost effective.

Wherever guideways are located above or near roads, ladder trucks can be used to rescue stranded passengers. If permitted, walkways would only be necessary on bridges or wherever no road was adjacent. If vehicles can run a short distance on battery power or be pushed by another vehicle, then the requirement for egress at all points is lessened. Also, helicopter rescue is possible where no roads are adjacent.

The infrastructure required depends on the mean time between failures, or MTBFs. If, for example, the MBTF of a vehicle in the case where it is stalled and cannot be moved by another vehicle, is 500 years, then it could be cheaper to send out a helicopter when necessary than to build egress walkways.

Evaluation criteria

- Death and injury rates should be as good as in other transit modes.
- The safety methodology should be validated by an independent firm to confirm that the predicted accident rates are realistic.
- Vehicles must permit emergency egress.
- Egress must be available from all points on the guideway, whether by walkways and ladders, helicopters, or rescue trucks.
- Vehicle must be fire resistant.
- The system must not impose hazards on people outside the system; i.e. the guideway right-of-way must be fully protected from other uses by being elevated, fenced off, or otherwise protected.
- Civil structures located near roadways must resist the force of a crash of the heaviest vehicle permitted on the roadway, OR must be built to withstand impacts according to the local regulations.

- Downed or impassible guideways must be detected, and no more than two vehicles may enter the danger zone from each direction after the condition occurs. (This requirement limits the number of unaffected vehicles unnecessarily thrown into a danger situation, but does not limit the size of the original event.)
- Persons who use wheelchairs and can travel independently, should be able to exit a stalled vehicle without any more assistance than other users.
- In a power failure situation, vehicles can be self-propelled, at least to the nearest station or egress point.

Examples of safety features

Some vendors provided information on safety features. We didn't ask all vendors for this information, so the following should be considered just some examples of how some vendors have handled safety requirements.

- MegaRail and MicroRail –

  All vehicles are equipped with emergency exit doors in each end to allow passengers to exit stalled or burning vehicles to emergency escape walkways located between the bottoms of the two guideway rails. Seats fold up and to the side to create emergency aisles inside the vehicles. The escape doors hinge down to provide escape ramps from the vehicle floor to the escape walkways. Passengers can move through stopped vehicles to reach guideway emergency exit points.

  All vehicles are equipped with emergency battery powered lighting inside and outside at the emergency exit doors.

  The emergency escape walkways enable safe passenger escape from stalled vehicles without assistance from emergency personnel.

  The emergency escape walkways consist of stainless-steel; open wire mesh stretched between the bottoms of the guideway rails. The enclosed guideway rails serve as wide guide rails to prevent escaping passengers from falling from the walkway. The weather guards on the inside sides of the rails provide full protection from electric power rails that are mounted inside the rails.

  Persons using wheelchairs can escape *unassisted* from these vehicles because the egress doors form ramps onto the wire mesh.

- Higherway –

  Vehicle includes passenger restraints (seat belts). The company chose to design to allow accidents, rather than to design for making accidents impossible. See discussion above.

  Vehicles are able to back up to the prior station on battery power in the event of a power failure.

- Frog – Each vehicle is equipped with two obstacle detection sensors. Both look ahead 30 meters with an 100 degree angle. The detection fields are split in a 'slow down' and 'stop' zone. Once an obstacle is picked up a vehicle will at first slow down and totally stop when getting to close to the obstacle. At that time a video image of the obstacle will appear on the supervisory computer so the supervisor can determine the action that needs to be undertaken. The system includes two sensors to avoid 'ghost obstacles' that were determined a problem in the pilot projects.
- Taxi 2000 – Vehicles can advance to the next station on battery power in the event of a power failure.

Operational characteristics

Evaluation criteria

- Vehicles are available for exclusive use by an individual or a small group traveling together by choice.
- Direct origin to destination service is offered, without a necessity to transfer or stop at intervening stations (i.e., “non-stop” service).
- Service is available on demand rather than on fixed schedules.
- System can carry unattended cargo.

Evaluation

The minimum requirements are met by all vendors, by definition; systems that could not operate in this manner were excluded from the report. Other notes about operational characteristics follow, although these issues will not be examined in detail in this report.

- Ticketing – We have read a variety of approaches to ticketing, and there are important issues about privacy and control to be considered. PRT user payments are complex compared to traditional transit, and a key factor in public acceptance. Therefore the proper design of the payment system is a key factor in the system design, not to be underestimated.
- Methods of circulating and storing empty vehicles is vital to ensure low wait times, and is a key part of the control system.
- For those systems that require a special vehicle dispatch for a wheelchair user, the network management algorithms must provide those vehicles, on average, with the same level of service as regular vehicles, in accordance with ADA (US).
- Cargo would probably be carried by cargo vehicles, and would possibly use a different set of stations, or at least use cargo berths at the passenger stations.

Flexibility, risk

Evaluation criteria

- The system must be deployable at a minimum useful installation size of about 1-5 km in combined length of network segments, so that the risk of deployment can be kept very low.
- The system must be alterable by adding new segments, switches, and stations.
- Multiple manufacturers must be available from which to procure components; therefore, the manufacturing specifications must be available to the operator.
- The proof of performance, including safety and reliability, must be sufficiently established prior to the first passenger served. However, it may be achieved in a variety of ways, which may change during revenue operation, as long as ongoing proof of performance is conducted. (For example, safety may be ensured initially by running very slow with very large separations, and then gradually running faster and closer as more analysis demonstrates safe and reliable operation. In this way the vendor can avoid the very large expense of testing using a realistic large-scale network over a long period of time.)
- Since no PRT system is operating, the buyer will incur technical risks. The system should use proven components and proven operating principles where possible to minimize the technical risks.
- The buyer should be able to procure the system with fixed price bid, to minimize risk of inaccurate cost estimates.
- Risk factors that make it impossible to predict costs accurately should be eliminated by a small initial deployment.
- The system should allow reconfiguration of elements that may have been installed in a bad location.

Evaluation

These requirements are not technical in nature, and are not evaluated in this study. However it is noted that the smaller and lighter the guideway, the less costly it would be to move it to a new location. In some circumstances where at-grade deployment is preferred, flexibility is most apparent with the systems that can drive on flat road-like surfaces – Frog and ULTra, most notably, and to some extent Urbanaut.

Cost and value

Cost requirements

- The value of people and goods moved is justified by the cost; i.e. the customer would choose the lowest cost alternative that gets people where they need to go. (This is really a procedural statement, which would come into play after the other requirements are satisfied.)

Component capital costs

We asked the vendors to provide this cost information:

List capital costs if available or estimated for these components: (a) cost per delivered vehicle (include all types if multiple types proposed); (b) cost per installed straight guideway-km in an elevated configuration with minimum road-crossing clearance; (c) cost of additional guideway components: switches, curves, and any other cost items; (d) cost tradeoffs by guideway clearance, soil types, or other variables, and any other cost-related notes. For item b, specify whether or not the estimates include command and control, transformer/substations, or any other ancillary structures and systems. Do not include the cost of stations, as these costs are assumed to depend more on the location than on the PRT system.

We failed to specify originally some additional cost details, which were filled in by later correspondence:

- express in 2001 US Dollars
- for large quantity manufacturing
- one-way guideway

***** Please do not compare these cost numbers directly, because different systems may classify costs differently. Contact the vendor for their latest cost estimates for a particular application. *****

Responses from vendors were as follows:

System	Guideway (M$/km)	Vehicle (k$)	Notes, Justification
Austrans			Au$20M/km[53]
Autran	1.3 (e)	20	costed by principal in company[54]
Cybertran	3.1 (bep)	100	costed by four separate large firms[55] and based on prototypes
Frog (CyberCab)	unknown	63	based on pilot project[56]
Higherway	2.0	unknown	preliminary estimate
MegaRail	1.3 (ep)	18	preliminary estimate
MicroRail	0.8 (ep)	15	preliminary estimate
Mitchell (ADA)	1.5 (ep)	see note[57]	cost based on bids by manufacturers of the prototypes
Pathfinder	12-15		includes stations; estimated by principals in company
Ruf	2.2	20	estimated by principal in company
SwedeTrack			unknown
Taxi 2000	1.6 (ep)	26	costed by a university and three other large firms[58]
ULTra	1.5	50	actual cost of prototype
Urbanaut	4.5 (ep)	1300 [59]	

[53] Austrans did not supply requested cost information.

[54] The cost estimates for Autran were prepared by Van Metre Lund who is not an expert at cost analyses. However, he has had 50 years of experience in conducting research and making analyses with respect to a wide variety of electrical, electronic and mechanical systems and components and with respect to patentability, infringement and alternative designs that might avoid infringement. In all such analyses, costs have been considered, oftentimes being a very important factor. Manufacturers of all components were consulted for costs.

[55] A number of costing studies have been performed on the CyberTran system and its components. These include: (1) Idaho National Engineering and Environmental Laboratory: The INEEL has been constructing one-of-a-kind test facilities for 50 years. The INEEL estimate was made from the ground up and based on the basic components, material requirements, and automated control systems required. (2) Morrison Knudsen Corporation estimated that the CyberTran system could be constructed for 10% to 50% of the cost of conventional rail transit systems. (3) SAIC did a preliminary evaluation of the CyberTran system costs for their own internal decision making processes and validated the estimates made by the INEEL. (4) Parsons Brinkerhoff performed an evaluation of just the guideway structural cost (not including rails, power, or control subsystems) and arrived at a cost of $2.8M per system mile. This was part of a system study by PB for the city of Boise, ID. (5) Costs of the sensors and control subsystems are based on previous experience in building the control systems for nuclear test facilities at the INEEL. (6) Vehicle costs have been evaluated from several directions – from buildup of basic components and their costs, experience in building the two test vehicles, and comparisons with other vehicles based on common transportation metrics.

[56] Costing studies were performed by Frog Navigation Systems and the operators of the pilot projects. Basis of the costing were the costs made in the development and the delivery of the pilot projects.

[57] Prototype costs are quoted at 35 k$ per vehicle, but the principal estimates that quantity manufacturing would bring the price to $7,500.

[58] Taxi 2000 underwent four costing studies, which have been updated to the present time, mostly with the transit price index, but taking into account advances in electronics and computers. (1) The first cost estimate was developed by a team at the University of Minnesota in 1982-3. (2) The second cost estimate was developed by the Chicago Technical Office of Davy McKee Corporation in 1984-5. (3) The third cost estimate was developed in cooperation with United Engineers and Constructors, a wholly owned subsidiary of Raytheon Company, the Raytheon Equipment Division, and with the assistance of a Project Engineer at the Volpe National Transportation Systems Laboratory in 1987-8. (4) The fourth cost estimate was developed by a team of companies led by Stone & Webster Engineering Corporation in 1991-2 in a $1.5 million study for the Chicago RTA. The team included Hughes Missile Systems Division on control and TDM, Inc., Detroit, on vehicles.

[59] Cost was only provided for the "large intermediate sized vehicle" which carries "10 times more passengers than the PRT".

Notes on table – what costs are included in estimates

(b) bi-directional
(e) electronic guideway based control system
(p) power substations, transformers

Additional component costs supplied by vendors

- Autran – The cost per delivered carrier vehicle has been estimated at $12,500. The cost per PRT/GRT cabin has been estimated at $7,500 for a total of $20,000 per vehicle-cabin combination. (The cost per car-carrying platform/pallet has been estimated at $2,500. The cost per dual-mode car has been estimated at $40,000.) The guideway design is such that the cost for an installed curved guideway is little more than for a straight guideway.
- Cybertran – Switch costs an extra $10k; central control system costs $1M
- Frog – Larger vehicles cost $156k (10 passenger) and $188k (20 passenger). Use of Frog on existing pavement would require installation of magnets in the pavement at costs insignificant compared to other capital costs listed.
- MAIT - The major capital costs will be those of the component systems. However an essential aspect of the concept is that the cabin will be detached from the carrier and moved to ground level for passenger and goods access. We anticipate that this will bring a significant cost advantage. We also anticipate that the components of the network can be chosen to suit the type of traffic; for example low density segments will use cheaper low capacity carrier systems.
- MegaRail – Larger GAT vehicle costs $20k. Curved guideway is 50% more expensive at $2M. Switches are $38k extra.
- MicroRail – Curved guideway is 80+% more expensive at $1.5M. Switches are $23k extra.
- Ruf – Larger maxi-ruf vehicles cost $45k. Please note that far fewer miles of guideway is needed than for a pure PRT system because of the dual mode nature of RUF.
- ULTra – Estimates that control and power add about 30% to guideway costs.

Station cost estimates

- MegaRail estimates $105k - $0.5M per station, depending on size. MicroRail estimates are slightly lower.
- Ruf (and any other dual mode system) could have cheaper station costs, since stations could simply be flat areas like bus stops, having no guideway.
- Taxi 2000 estimates $240k

Maintenance facility cost estimates

- Mitchell estimates $1.9M
- Taxi 2000 estimates $600k, including control and administration

Installation costs

The installation costs that are not reflected in the capital costs above are costs of changes to utilities, streets, other infrastructure that would be necessary in the installation process. These could vary significantly from one system to another, because the sizes of guideways and supports differ.

Choice of a system would depend on site-specific cost quotes, which must take this into account.

Operations cost

Issues around operations cost are:

- life expectancy (replacing components)
- actual operations cost (personnel, energy, real estate, security, administration)
- maintenance cost (cleaning, repair)

This report will not include a detailed study of operations costs, but some vendors noted these cost advantages of their systems. Of course, many of the advantages noted apply equally as well to other systems

- General – Guideways with no moving parts. Self-diagnosing system health monitoring systems. Preventive maintenance plans. Autonomous vehicles can easily be removed and repaired, and the fleet size does not need to stay exactly the same at all times.
- General maintenance advantages of PRT compared to larger APMs (noted by Taxi 2000):
  a) A major advantage relative to large-vehicle APM systems is that the maintenance float is much smaller, about 2% based on our estimates of MTBF, which are detailed in paper #16 in the Publications section of www.taxi2000.com. The maintenance float for large-vehicle APM systems is typically about 20%.
  b) Smaller vehicles require correspondingly smaller space and smaller handling facilities.
  c) More smaller vehicles means higher quantity production, which lowers all unit costs.
- Austrans, Taxi 2000, and ULTra - Components are off-the-shelf industrial and automotive. They are cheap, readily available and are of proven reliability. In addition as they are already in wide use in a variety of applications they are well understood by technicians and fitters. This means that there is a large base of skilled personnel who could readily maintain the system with only modest training requirements.
- Autran - The system uses steel wheels, a turn control system that minimizes friction and wear and is otherwise designed throughout to minimize wear, stresses and fatigue and to otherwise obtain a long operating life.
- Cybertran - CyberTran is designed with simple, rugged mechanical components (steel wheels, wheel bearings from Class 8 heavy trucks, heavy duty truck power transmission components, etc) to have a high MTBF. When a component does fail, the vehicles are designed for rapid removal of the component and replacement with an operating component. Maintenance on the removed component can be done with out-source contracting, decreasing the need for high fixed cost maintenance organizations. Steel components of the system are fabricated from Cor-Ten type alloys that oxidize into a self protecting coating and require little or no maintenance.
- Higherway - The complexity of the system is mainly in the vehicles, which can be maintained by robots and people at ergonomic workstations in controlled climate and good lighting. The motor wheel tires can be resurfaced at low cost an indefinite number of times.
- MegaRail - Stainless-steel rail & station structure - No painting or rusting. Smooth; steel traction rails - Low tire wear. Direct-drive electric motors - No gearboxes.
- Mitchell - The simplicity of design requires technical competence of an electrician or average mechanic for most servicing of most components.
- Pathfinder - Light weight modular composite vehicles and power systems. Battery power which eliminates guideway power system. Light weight (14X18 inch) steel guideway. Onboard system control, reduces central control complexity. Enclosed guideway running surfaces eliminates guideway snow removal.

Cost evaluation

Component cost evaluation

A review of the component costs yields these results for PRT in general:

- Most guideway costs are in the range of $1.5 to $3.0 M per km
- Most vehicle costs are in the range $26 to $50 k.
- We note that a lot of work has gone into costing, and that the results of those separate studies for different systems yield costs in the same ballpark. Therefore we accept the cost ranges given as legitimate by a factor of 2.
- Those systems that have unusually low cost estimates are preliminary, and underestimating is normal in earlier phases of development.
- Frog has a higher vehicle cost, but it shifts its costs away from the guideway and into the vehicle relative to other systems, and the system could be cheaper, depending on the location. They have not costed elevated guideways.
- Cybertran has a very high vehicle cost of $100k, for its 6-passenger vehicle, and we have no reason to doubt its accuracy.
- Cost of curves may be up to 50% more expensive, but this is unclear at this time.
- Cost of stations depend more on the location and other factors besides the PRT technology, but can be estimated at $250k.
- Central control, communications, switches, and a maintenance facility are small costs compared to guideway construction (assuming at least 10 km of network), so can be left out of preliminary estimates.

Capital cost of 10-km system (system-independent)

A customer could reasonably expect to procure PRT at the rates listed below, or could use these for urban planning purposes. The customer could multiply the final result for a 20-km system, 30-km, etc. for a very informal method of costing PRT. The table is listed for 10-km, which is the distance of all the network segments added up.

Component	**Unit Cost**	**Number**	**Total (k$)**
Guideway – straight	2,300 k$/km	8	18,400
Guideway – curved	3,400 k$/km	2	6,800
Vehicle	38 k$ each	100	3,800
Stations @ 2/km	250 k$ each	20	5,000
TOTAL			34,000

Therefore capital costs might be around $34 M for a 10-km network. (for preliminary planning purposes)

That's $3.4 M per km, or a little over $5 M per mile.

Characteristics of a specific installation

After selecting technology candidates, a city or operator would need to evaluate specific installation options against requirements. We suggest these requirements, but of course they cannot be evaluated in the abstract.

Evaluation criteria

Cost and value

- The system with the least actual life cycle cost per unit of service, which can meet all other requirements, should be chosen.
- Cost may be reduced by utilizing existing tracks, bridges or support structures.
- The system should serve actual existing origins and destinations (It should go where people want to go.)
- The system should improve on existing travel options (faster, cheaper way to get between actual travel destinations)
- The capacity of the system should at least match the projected ridership.
- The system should connect with other modes. Total transportation flow modeling can be used to show how the new system fits in with existing assets and corridors.

Physical characteristics

- Stations must be wheelchair accessible.
- New rights of ways should be minimized, and displacements of buildings should be avoided.
- The system should fit into the urban form and character.
- The geometric requirements (radius, grades) of the system should fit within the constraints of the service area.

Negative impacts

- The system should minimize real or perceived barriers dividing neighborhoods.

- The system should not impede other transportation, e.g. roads.
- Construction impacts should be minimal.
- Impact to historic structures should be avoided.
- Impact to wetlands or other sensitive land should be avoided.
- The system should be planned in a way that is sensitive to changes in future land use based on new transportation option.

Appendix A: Vendor Questionaire

The following letter was sent to PRT vendors to request information about their systems. The letter was followed by several rounds of clarifiying questions and answers.

Letter

I am representing the PRT committee of the Advanced Transit Association (http://www.advancedtransit.org) and I am writing in regards to our effort to develop a report on the current developmental status and outlook for PRT (Personal Rapid Transit).

I am asking you to respond to 19 questions about the XXX system, for inclusion in our report. We will compare the responses of different vendors, and we will attempt to show the results in such a way that a planner or potential buyer would understand the benefits and differences of each system. Your contact information and web address will also be included.

I want to reassure you that the committee members are generally optimistic and knowledgeable about PRT. There will be no quantitative evaluation or ranking of the systems, and no attempt to determine the "best" system.

Thank you for your help. More information and the list of questions are below.

Ian Ford, ATRA PRT committee

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Request for PRT System Information

The Advanced Transit Association (ATRA) is in the process of producing a new report on the status and potential of Personal Rapid Transit (PRT), to update the report that ATRA developed in 1989. The PRT report committee of ATRA is therefore requesting that developers of PRT systems submit information on their systems for inclusion in the report.

Any developer may submit information; however we will only include systems that have undergone some amount of rigorous engineering, and will not include systems that are in the conceptual phase.

Developers of dual-mode systems should submit information pertaining to how their system would operate in captive mode, or how the PRT portion of their system would operate. Additional benefits of dual-mode will be noted in the report but the focus of the report is PRT and we will not evaluate dual-mode characteristics of systems.

Developers of GRT systems may submit information pertaining to how their system would operate in PRT mode, if operating as PRT could be feasible and cost-effective.

Systems must meet the following basic criteria for PRT systems, which will be assumed, and you do not need to list these in your submission:

1. Fully automated vehicles (i.e., without human drivers).
2. Vehicles captive to the guideway, which is reserved for the vehicles.
3. Small vehicles available for exclusive use by an individual or a small group traveling together by choice.
4. Small guideways that can be located aboveground, at or near levelground, or underground.
5. Vehicles able to use all guideways and stations on a fully connected (a "coupled") PRT network.
6. Direct origin to destination service, without a necessity to transfer or stop at intervening stations (i.e., "non-stop" service).
7. Service available on demand rather than on fixed schedules.

Please submit information in the order and format listed here:

1. Description highlighting the unique points of this system versus other PRT systems - 100 words. (No need to repeat the benefits of PRT over other modes of transport.)

2. How much money has been spent so far in developing the system, over how many years?

3. Describe the stage of development of the system - for example, state if detail engineering drawings are done, if a prototype has been built, etc.

4. List capital costs if available or estimated for these components: (a) cost per delivered vehicle (include all types if multiple types proposed); (b) cost per installed straight guideway-km in an elevated configuration with minimum road-crossing clearance; (c) cost of additional guideway components: switches, curves, and any other cost items; (d) cost tradeoffs by guideway clearance, soil types, or other variables, and any other cost-related notes. For item b, specify whether or not the estimates include command and control, transformer/substations, or any other ancilliary structures and systems. Do not include the cost of stations, as these costs are assumed to depend more on the location than on the PRT system.

5. List any maintenance cost advantages relative to other systems.

6. What is the basis and credentials of the costing study and who performed it?

7. What are the credentials of the engineering team?

8. What is the vehicle capacity (standing, seated, wheelchairs, etc.)?

9. What is the line capacity in vehicles per hour? (include other notes on system capacity here)

10. What is the design speed and maximum speed?

11. What are the dimensions of the vehicle and guideway components? (include standard and variances)

12. What is the noise level if known?

13. What is the power requirement per vehicle at the design speed? (in kW)

14. Is it suspended, supported, or both/either?

15. What is the type of drive system? (e.g. rotary two-wheel drive, linear induction motor, etc.)

16. What is the type of guidance and switching system? (e.g. sidewheels, maglev, guideway-activated switch, etc.)

17. How does the system meet the accessibility requirements of the Americans with Disabilities Act for stations (Appendix A of 49 CFR part 37) and vehicles (49 CFR part 38)? In particular, are there unique features that would necessitate a special set of requirements (under 49 CFR 38.171(c))? If so, what would those requirements be?

18. List additional characteristics that don't fit in one of the categories above.

19. List references to web sites or published material about your system, contact information, etc.

(END OF REPORT)