

VECTUS PRT CONCEPT AND TEST TRACK EXPERIENCE

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Abstract

PRT, Personal Rapid Transit, is a transportation concept with small vehicles on a low-weight structure offering a high level of service to its passengers. Vectus, with operations in Korea and Sweden, is at the forefront of PRT technology. Vectus has built a test track in Sweden where the system functionality and performance has been verified. Authority approval has been obtained including a complete safety case. The test track concept and the key features of the Vectus system are described along with the current operational experience. This includes two full winter seasons, proving the system's capability to cope with various ice and snow conditions. Test activities are now in the final stages of reliability and endurance testing, verifying the long term operational aspects of the system.

Introduction

PRT has been discussed as a concept for decades, and extensive research and various investigations have been done to determine its potential as a transportation system for tomorrow. Vectus is one of the few systems that has been built and that has experienced full testing. Vectus is able to fully demonstrate a PRT concept (see Figure 1) with the following key features:

- Flexible mechanical guidance system with:
- Vehicles that are captive on the track
- Vehicles that are mechanically guided along the track
- Vehicles that are mechanically steered through switches
- Headway down to 3 seconds, fulfilling brick-wall stop requirement, also in winter conditions
- Top speed about 45 km/h
- Asynchronous control system, maintaining highest performance under all operating conditions

- Dynamic moving-block vehicle separation maximizing vehicle flow and allowing speed restrictions without capacity reductions
- Distributed, reliable control with dynamic routing capable of virtually unlimited expansion
- Full winter operability with linear motor technology
- Complete and approved safety case
- Full RAM and LCC analysis

Vectus has built and operates a test track in Uppsala, Sweden. It has 400 meters (m) of track, three vehicles and one station. The test track construction started in the spring of 2006. In December the first trial runs were made with a chassis to verify the propulsion system and basic controls. The first complete vehicle arrived in the summer of 2007. Since then, tests and verifications have been made, step by step, with increasingly more complex functionality to cover all aspects envisaged to be needed in a commercial application. A thorough design process has been applied, covering safety, reliability etc., not only for the test track itself, but also for a generic PRT system. The test track has been approved by the Swedish Rail Agency for operation with passengers.



Figure 1. First complete vehicle in full operation, summer, 2007

Vectus Test Track

The test track built by Vectus in Uppsala, Sweden is a key component of Vectus PRT development. Prior to the test track being built, various studies had been conducted over several years. One important aspect of these studies was the overall control and the logistics solutions of a real system, which were studied using advanced simulation tools. Based on these studies, the key parameters for a commercially viable system were identified. From these system characteristics, the different sub-systems and key technologies were selected. Again, for selected areas, more studies were conducted in

test rigs, simulators, scaled models, etc. Most of these studies were conducted in England and Sweden. It is noteworthy that Vectus PRT development did not originate from a technical concept for e.g. track and vehicle, but rather from a rigorous top-down process. Development began using the complete system as the main focus with special considerations for safety and control aspects. Systems and components were then selected to suit these criteria.

Having these steps accomplished, it was time to build the first full-scale system in 2005. Selection of a suitable site was important; a site where there was availability of good communications, possibility for testing in winter conditions, internationally recognized authorities for approval, and complementary university and industrial structures. The site selection process finally ended with the choice of Uppsala, just north of Stockholm, Sweden.

The test track configuration (see Figure 2) was carefully chosen to be as small as possible but still with the capability of proving all aspects of the full scale system. The total length of the track is about 400m. The outer loop allows speeds of up to 12.5 m/s (45 km/h). The track in the curves is cambered. The inner loop has a station with two platform positions. The tracks entering and exiting the station are fairly long to allow merge operations at full speed. Acceleration leaving the station is 2 m/s^2 . Maximum retardation using the independent emergency brake is about 5 m/s^2 . The headway can be as short as 3 seconds. The test track has been designed, built and commissioned with a group of Swedish and British companies as the key subcontractors.

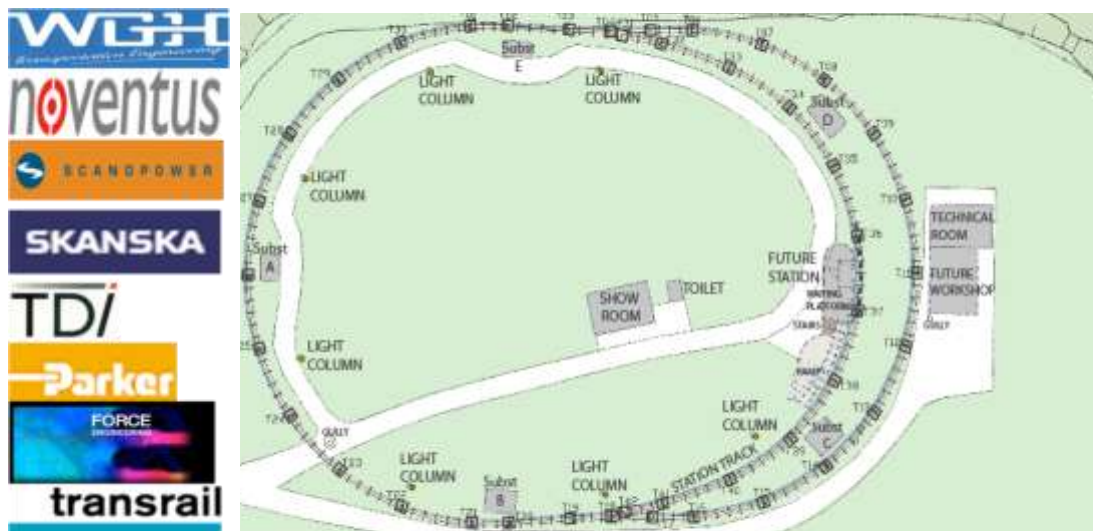


Figure 2. Top view of the test track.

The safety process has been an integral part of the test track design process. Authority approval has also been on-going from the very beginning with the Swedish Railway

Authority, with the same set-up and general requirements as are applied when e.g., building a new metro (subway).

The detailed planning for the selected site in Uppsala started in late autumn, 2005. In April 2006 the ground-breaking ceremony was held, and then the first track sections were delivered in August. Running tests with only a chassis vehicle started in December, 2006 and the first run around the outer loop was accomplished just before Christmas. In the spring of 2007 the inner loop and the station were finalized. The first complete vehicle arrived on-site in the summer of 2007 and the second vehicle arrived shortly afterwards. The system was displayed for a larger audience at the PRT seminars held in Uppsala in the autumn of 2007.

Finalization of the commissioning, safety case, and various testing led to an approval of the safety case in December, 2007, approval for test runs with visitors in March, 2008, and full approval with multiple vehicles and third party passengers in September, 2008.

The test track is a complete and genuine representation of a full scale PRT-system, in particular the function of the control system. The vehicles have been given a realistic design for the look and feel of a real application, whereas the track and parts of the electrical installations have been selected for ease of testing and quick installation rather than from an aesthetic point of view (see Figure 3).



Figure 3. Test track with three vehicles and sample 2-berth station.

The main purpose of the test track is to verify the technical design, and particularly the control aspects. It also makes it possible to carry out a complete safety case including verification and validation on a real application. Another key aspect has been the authority process itself, to identify the “real” requirements for all aspects of a system. There has been ample thought given to various passenger aspects, such as access for the disabled and guidance for the visually impaired. There is an example of

a ticketing system, and complete passenger interfaces in the vehicles with displays, intercom, etc.

Another objective is to determine long-term performance. Detailed modeling of the reliability and availability and life-cycle cost were part of the design process, which requires verification. The test track also provides a proving ground for continued development, both for Vectus internal R&D as well as being able to test client-specific modifications at an early stage.

The Vehicle

The vehicle for the test track was designed to give a realistic impression of form, shape, and function. It has low weight and high rigidity. It is vandal resistant, easy to clean, maintain, and repair with no sharp corners or edges. The cabin's interior design is determined by safety requirements and complies with European disability discrimination and accessibility legislation. The layout of seating, grab handles and control devices follows recommended ergonomic practices for mass transit vehicles.

Level access is provided between the platform and cabin floor (see Figure 4). There is a pair of externally sliding bi-parting doors on each side of the cabin. The doors and door aperture curve around into the roof as close to the center line of the vehicle as possible in order to create the greatest possible headroom for passengers when entering the vehicle.



Figure 4. Vehicle access from the station platform.

The interior of the cabin is quite spacious (see Figure 5). The individual seat units are sufficiently wide to provide generous shoulder room for up to four passengers. The seats are fitted with integral 3-point seat belts and headrests and the seat base is angled to help restrain passengers during rapid periods of acceleration and deceleration. An attachment system for a wheelchair and baby or child seat (e.g.

between the two adult seats) can be provided. Interior styling will be developed according to customer specifications.

LED reading lights are available for each passenger which can be adjusted individually with control buttons on the control panel box located between each pair of seats. The control panel box incorporates illuminated disability-compliant push-buttons taken from public transport standard components. The panel also incorporates the vehicle's door control button and alarm call button that activates communication with the system operator. An LCD display/touch screen can also be incorporated for passenger information and entertainment system. The interior temperature is thermostatically controlled with an HVAC (heating, ventilation and air conditioning) unit which can also be adjusted by the passenger.

A "FeONIC, Whispering Windows" sound system, using advanced "magnetostrictive" technology, provides passenger audio. This system effectively uses the whole interior body shell as a loudspeaker.

The chassis's wheel arrangement and emergency brake system have been designed to meet operational and safety requirements with a minimum of equipment and with as low a building height as possible (see Figure 6). Vectus uses hard tires running on steel track to minimize rolling resistance, giving low energy consumption and less sensitivity to vehicle weight.

Vectus employs switching wheels in the chassis for directional control in junctions. One of the safety advantages of mechanical vehicle-based switching is that direction selection can be made well in advance, before the junction, allowing time for the activation mechanisms to be secured in position and locked. There is also positive mechanical guidance and locking between vehicle and track throughout the whole junction. There are no moving parts at all in the track.

Effective braking in all conditions is a key function to provide a system with short headway and still maintain a brick-wall stop requirement. Specially-developed spring-applied caliper brakes acting directly on the surfaces of the guide rail produce a constant brake force under all track conditions.



Figure 5. Vehicle interior with display panel between individual seats and roof-mounted ventilation unit.



Figure 6. First chassis tested for clearance on a section of track.

Track

The Vectus design philosophy has been to develop a simple rail and guidance system independent of the support structure. This allows the architect or system designer the freedom to develop the type of support structure most suitable for the application. The track design at the test track was selected primarily for testing purposes. The guidance system (in blue, see Figure 7) is mounted on a steel support tube as the main structural component. Only the top portion is required (blue) when being installed inside a building or in a tunnel, giving a low overall height requirement. A commercial design may look quite different, while still having the same guidance concept.

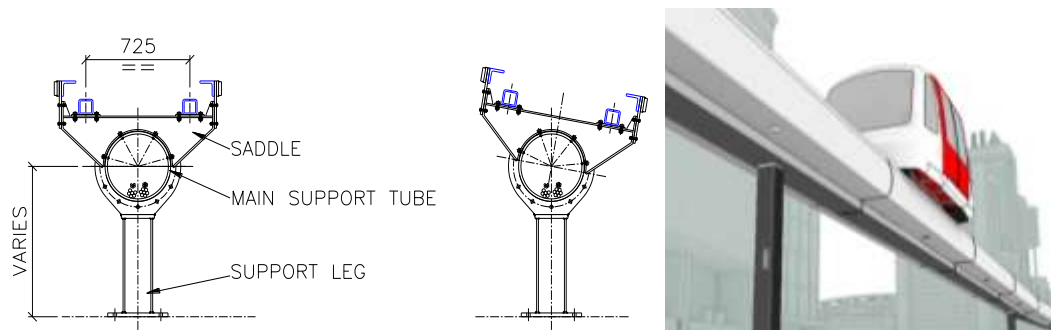


Figure 7. Test track guidance system in blue on steel tube support structure. To the right above is a possible future design of a track.

The Propulsion System

In order to run with a short headway, and with minimal margins for unwarranted safety brake applications, precise and consistent performance of the drive system is a vital component. Linear induction motor (LIM) drives have often been the choice in various PRT concepts. This is also the case in the Vectus system. Vectus has built its

own control system to be able to handle all types of propulsion, and for the test track the choice fell to an in-track LIM propulsion solution.

The main reason for choosing an in-track LIM propulsion system was the capability to handle snow and icy conditions without any performance degradation. Linear motors give the same thrust regardless of the available friction between the wheel and the rail, both in acceleration as well as in braking.

Another advantage is the elimination of a current collection system which improves reliability. This is also a safety improvement, further reducing the risk for electrocution by having all electrical installations “safe-to-touch” by means of conventional cables.

In the ramp leaving the station, motors are spaced twice as close as normal to provide the thrust required for the vehicles to accelerate. At the test track, the blue buildings (see Figure 8) contain the electrical equipment and the propulsion inverters. Cables are routed from the building to each LIM. In a commercial application this will be integrated into the track using specially-built, small-size inverters fully utilizing the short duty cycle for each LIM.

The Control System

The control system is the most important system for a commercial PRT application. Vectus has performed rigorous analysis of the requirements of the total system together with leading experts in the fields of logistics and transportation optimization. In the early stages, Vectus developed their own PRT simulator and tested various types of large PRT networks to verify functionalities and performance of different control schemes.

The results from the analysis can be divided into four groups of requirements.

Distributed and scalable control.

A distributed system means that the control is carried out locally for a limited



Figure 8. Linear motors in the acceleration ramp out from the station in Swedish winter weather.

part of the system. If there is a fault, it only effects a small part of the system. The rest of the system will continue to work. With the distributed system there is no increase in the load for each individual control segment when the system is expanded.

Asynchronous Control.

With asynchronous control the flow of vehicles is handled as they travel along their path to their destinations. Merging of vehicles is managed as required on a local basis. Occasionally there may be a need to slow down to facilitate merging in switches; there may even be short queues along the route at times. Travel time may be prolonged by a few seconds, but the overall capacity of the system is maintained, which is essential to the overall ability to transport passengers during periods of high system loads (rush hours, events, etc.).

Vehicle Spacing – Dynamic Moving Block.

A moving-block system is superior to any fixed-block vehicle protection system, even if the fixed blocks are very short. The moving-block system continuously updates each vehicle with information on the position of the vehicle in front of it. With this information, each vehicle can run with the shortest allowed vehicle spacing based on the worst case brake performance. With a dynamic moving block, the distance between the vehicles can also be varied depending on the speed of the vehicle (or rather the actual stopping distance depending on the speed). At lower speeds the vehicles run closer to each other; at higher speeds the distance is increased. This allows queuing on the track if required (see Figure 9) without backing up the system for long distances (the vehicles will stop almost bumper to bumper instead of one in each fixed block). Most importantly, it enables varying speed along the track, e.g. in curves, without impacting the flow of the vehicles in that track section, hence overall capacity of the system remains.

Optimal Control.

The above systems are the building blocks in providing safety, as well as adequate capacity. Then it is a matter of optimizing the logistics of the vehicles. Vectus has an adaptive-control which learns from travel patterns of traffic from previous days. This can be manually altered in the event of e.g., delays in a train arriving at one station, special events generating large crowds, etc. Effective empty vehicle management is another key feature, reducing the mileage of empty vehicles.



Figure 9. With the dynamic moving block control, vehicles can run with shorter distance between them at lower speeds.

Safety

The overall safety process in Vectus' PRT project follows the standard EN 50126/IEC62278 "Railway applications – specification and demonstration of reliability, availability, maintainability and safety (RAMS)". This is a standard that is well-implemented in the European Union and defines a process to support the identification of factors which influence the RAMS of railway systems. This safety work has been an integral part of Vectus' development from the beginning.

A number of safety targets were formulated and are as follows:

- The safety level for the PRT system shall be better than the safety levels applicable for competing transport systems such as buses, trams and taxis.
- No single failures in the PRT system shall lead to an accident with serious consequences.
- The PRT system shall be designed so that passengers feel safe and secure during the whole journey, including their time in the station areas.
- The PRT system shall be built without any serious accidents during the construction phase.
- There shall be no accidents with human injuries during the test phase of the system.

For the overall PRT system the following risk acceptance criteria was agreed upon with The Swedish Rail Agency to be met by Vectus (and PRT in general):

- Maximum 0.3 fatalities per billion person kilometres for passengers in PRT system.
- A fatality risk of maximum $1 \cdot 10^{-6}$ per year for the most exposed third person.
- For each of the sub-systems, there must be documentation that there are no single failures that can cause a severe accident.

Safety work has involved various activities such as establishing safety plans and performing safety analysis, FMECAs (Failure Mode Effect and Criticality Analysis), fault trees, safety audits, etc. in order to establish a complete safety case. The safety case was completed in 2007. The required authority approvals to carry passengers were obtained in the spring of 2008.

Wherever applicable, the safety analysis has not only been done for the test track, “as built”, but also with considerations for a large, commercial system. The overall safety targets have been verified for a sample large system by performing a QRA (Quantitative Risk Assessment).

The QRA includes 78 different sensitivity calculations to verify the criticality of different input factors. For the larger system that was modeled, passenger risk is quantified to 0.165 fatalities per billion person kilometers, which is well below the acceptance criterion of 0.3 fatalities per billion person kilometers.

RAM and LCC

The RAM-process has resulted in the following:

- Generation of a qualitative and quantitative model of the PRT system, modeling the availability and reliability characteristics of all the components of the system, vehicle, track, station, etc.
- Comparison of system RAM characteristics to target values
- Contribution to a balanced design by identifying the main factors in providing adequate availability of the PRT system
- Early assessment of needs and possibilities for changes and redesigns based on a (preliminary) design phase RAM analysis
- Follow-up of RAM characteristics during test operation (see Figure 10)
- Input for maintenance planning, including definition of a necessary spare-part inventory



Figure 10. A full set of maintenance procedures has been developed that are verified during test track operation.

All relevant components in the system have been identified and each component has been assigned values for failure rate, MTTR (mean time to repair) and failure criticality. Wherever possible, sub-supplier data is used. However, most of the data is collected from generic data sources (IEEE STD-500, NPRD, etc.) and (in some cases) based on engineering judgment. For the control system, reliability is calculated using the reliability model RDF 2000.

The analysis for a typical commercial application has shown results in both station and line availability higher than 99%. System reliability is also very good, with corrective maintenance consisting of about 10% of overall maintenance. The vehicles account for about 75% of the total maintenance of the system. Items such as

the on-board batteries (24V for on-board control), speed encoders and other sensors on the vehicle, doors, and some of the hydraulics are the main contributors.

A simplified life cycle cost model has been done as well. In this model, parameters can be chosen for system size, operation hours, mileage, cost of labor, energy, etc. and a good quality estimate of the operational cost can be obtained. It uses the RAM analysis combined with spare-part costs as input for all corrective maintenance. It also incorporates the actual maintenance plan with costs for consumables as a basis for planned maintenance.

Operational Experience

One of the key challenges of PRT is to run vehicles with a short headway, and even more so, to be able to merge vehicles in a junction while still maintaining a short headway. With three vehicles on the test track this has been successfully demonstrated at nominal speeds.

Extensive testing has been carried out on all systems. Operation in winter conditions has been one key test area (see Figure 11). In quite dramatic conditions with extensive amounts of snow, and also in conditions with very difficult ice crust situations on the steel track surfaces, the vehicles have cleared their way and run with minimal problems (to the contrary of most other public transport in similar

situations). Most importantly of all, the brakes have also functioned under these extreme climatic conditions, and decelerations of more than 4 m/s^2 have been achieved even with the guide rail almost totally covered with solid ice.

Another important issue has been external noise. Measurements according to ISO 3095 (7.5 m to the side and 1.5m above top of rail) have been performed. Noise levels are just below 70 dBA at nominal speed, significantly lower than what is normally registered in LRTs and buses.

The propulsion system with the in-track linear motors has shown an actual performance very close to the initial calculations. Maintaining air gap has not been an issue at all and there has not been any need for re-adjustment or corrections of the LIM height settings in the track. No noticeable wear has occurred yet on the running wheels.

The main challenges that have been encountered at the test track have primarily been a result of geometrical constraints due to the limited size of the test track. The overall length of the track is relatively short, resulting in only short stretches of straight track, and it is not possible to have proper transition curves. The curve radii combined with the design speed require super-elevation for passenger comfort. This increases the transition-curve problem further. As a result of this, specific track alignment issues particular to the test track have been a complication in the testing and evaluation of some parameters.

The reliability and availability targets for the system have been set very high. So far, with approximately two years of trial operation, there have been very few failures actually requiring replacement of a component. As for the propulsion and electrical



Figure 11. Vehicle clearing its way in severe ice and snow at 5m/s.

systems, there has been only one faulty component, a communication board for a CAN bus (Controller Area Network), which was automatically diagnosed and repaired in a matter of minutes. The fault had no real impact on operation of the track,

and would have caused neither a stop nor a delay in a commercial application. The few components that have been necessary to replace on the vehicle have been speed encoders, some sensors, and batteries on a few occasions. There have also been the usual door problems, but so far these have been more of an engineering kind rather than actual reliability issues.

Conclusions

Vectus set out to build a test track for its concept for Personal Rapid Transit with several objectives in mind. One of the most important goals was to prove a control concept using distributed asynchronous control based on a dynamic moving-block vehicle protection system. Proving the function itself was not the only target, but also to make a complete safety case and to obtain approval from the relevant authorities. This has been successfully completed, along with safety approval for the other systems required for PRT, i.e. track, vehicles, station, etc., and also other aspects such as operation and maintenance.

The track, the vehicle, the switching mechanism, etc., have been designed to optimize an elevated PRT-system application. Safety, reliability and performance, with headways of 3 seconds at speeds of 45 km/h, have been key design targets taking into consideration weather conditions with snow and ice. The vehicles are captive to the track and employ positive mechanical guidance through switches as important safety characteristics. The Vectus PRT concept is adaptable to a variety of propulsion system solutions. The test track has been built using in-track linear motors for propulsion. Testing has proved that the functional and performance requirements set forth for a large scale PRT system can be achieved, including successful operation in a winter climate.

The test site has provided an opportunity for an increasing number of visitors to appreciate PRT's potential to provide an attractive and modern method of transportation which includes good passenger comfort, low external noise, and high levels of security. Ongoing activities include further testing to verify reliability and also evaluation of various operational aspects of the system.