A new paradigm for flexible and compatible on-demand transport solutions

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Abstract

The Personal Rapid Transit (PRT) system has recently attracted much attention as an efficient, sustainable, and green transport solution for accommodating personal transportation requests. PRT is generally defined as a small-capacity (e.g., 4–6 passengers) vehicle with fully automated driving capabilities for transport of passengers on a network of roads with on-demand and point-to-point transport capability. The objectives of this research were to identify a possible PRT implementation scenario to satisfy a variety of purposes, and to assess the system functionality and impacts on an application/system level using a testbed vehicle (i.e., modified golf-cart). The operational test using the experimental vehicle was performed on a pilot road network incorporating each sub-function of the system, designed for evaluation purposes. This small-scale demonstration enabled the evaluation of system functionality as well as identification of unexpected user requirements caused by its operation. In this study, the target specifications and system architecture of the Korean PRT system at a production level were also reviewed. Eventually, the evaluation results will be reflected in prototype production for further improvement.

Keywords: Personal Rapid Transit (*PRT*), *Inductive Power Transfer System* (*IPTS*), *magnetic marker-based guidance control, vertical transfer.*

1 Introduction

Public transportation systems with large transport capacity are efficient in operation and management, but are limited when it comes to providing demand-responsive transport services. In other words, mass transit systems inherently

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lack the ability to provide passengers with optimized direct routes, or immediate on-demand transport without time delays, because they transport in groups over scheduled routes. As a consequence, dependence on private cars has increased, which results in unacceptable levels of congestion and environmental concerns. In addition, demand for increased accessibility to destinations and better compatibility with existing transport systems is growing as the significance of transportation assistance has been recognized. Personal rapid transit (PRT) systems were initiated in an attempt to address the weaknesses of mass transit systems, as well as to offer services similar to a private car, such as privacy and independent scheduling [1].

Initially, the actual implementation of a PRT system based on its original concept failed, because physical and economic feasibility scenarios for its completion were regarded as unrealistic [2]. The reasons it could not be realized as envisioned by proponents were complicated by various factors, including financing, cost overruns, regulatory conflicts, political issues, misapplied technology, and flaws in design, engineering or review [2]. However, the concept still remains active, and thus ongoing efforts continue with alternative strategies for flexible and compatible applications.

To date, two PRT systems are currently operating: since 2010, the 10-vehicle 2getthere system at Masdar City, UAE, and a 21-vehicle ULTra PRT system at London Heathrow Airport since 2011. A construction plan for additional ULTra PRT systems was recently announced at Heathrow. This extension project, known as Q6, began in April 2014 and will run through 2019 [3]. The success of the ULTra PRT system has demonstrated the huge potential for PRT systems as a new transportation mode.

Besides these, numerous prospective PRT systems have been proposed but not commercially launched yet. The strategic urban transport policy for Korea is now at the point in the installation of the main line to transition to the expansion of branch lines. In connection with this, the Korea Railroad Research Institute (KRRI) in South Korea has moved ahead with implementation research into possible functionality at a production level in 2012, following a previous feasibility study conducted in 2011.

In the present study, we describe the unique technical features of the Korean PRT system and its possible implementation scenario. Furthermore, its economic and technical feasibility is reviewed by evaluation, based on a specific level of service and size suitable for a new transportation mode in Korea. Most importantly, operational validation was carried out by test-bed experiments to demonstrate the possibility of technical implementation of the functions proposed in this investigation.

2 Implementation scenario

The major impediments to commercialization of a PRT system are its high cost and the inefficiency of constructing independent infrastructures solely for PRT vehicles, such as guideways, switches, stations, and a control system [2]. In addition, the structures of the Korean PRT system need to be devised to make them less visually obtrusive and to minimize their effect on the traffic flow of other transit routes. As a result, the driving mechanism of the Korean PRT vehicle basically resembles a small automated electric car, and the vehicle employs rubber tires running on an open guideway, with guidance control based on the detection of magnetic markers installed along a reference line of pre-designed routes. Elevated guideways or near-surface tunnels are considered necessary to prevent congestion and ensure safety, such as at crossroads. The alternative, where a harmonized connection with other public transportation systems on an existing road network is impossible, is to build separate operation routes for the PRT.

Due to high demand for a green and sustainable transport solution, it is imperative to speed the transition to electric-powered transportation. However, battery (or supercapacitor) powered vehicles pose difficult technical challenges in energy management due to their low energy density and large volume. Also, while integrating guideways with a power supply by physical contact with a power line can reduce vehicle weight, it can lead to isolating PRT routes from other means of transportation, causing less compatibility, and increasing costs arising from line construction. Thus, a contactless power transfer system based on the inductive power transfer (IPT) principle is one of the more promising options. IPT stems from a previous road powered electric vehicle (EV) [4]. Nevertheless, the IPT is economically inefficient for application to an entire route because of its high construction cost, and energy losses due to leakage of the magnetic flux or in the transmission line. Also, the PRT system is usually suitable for relatively short-distance transport due to its transport characteristics.

In view of these considerations, an IPT-Supercapactor hybrid energy supply system was proposed in this study. The Korean PRT vehicle picks up power during a short time in a stationary position at the station, from road-buried power rails, speed-charging its supercapacitor. Then electric power is supplied to the driving motor from the supercapacitor during driving mode. The capacity of the supercapacitors should be determined according to the size of the road networks.

Finally, to enlarge the possibility of extended application for a variety of purposes, an innovative concept was proposed in the Korean PRT system, the vertical transfer of the vehicle operating on road networks. This apparatus was initially designed based on the vertical circulating conveyors with steel chain frequently used in logistics [5]. Its advantages include non-stop loading and minimum head-way time. Most importantly, it can ensure the stable and reliable transfer of a fully loaded PRT vehicle operating on a road network. This trait introduces a new paradigm for the operational mode of the PRT, to meet the particular demands of certain environments, such as the transfer of passengers to other transportation modes between/inside buildings (e.g., a complex transfer center). Fig. 1 shows an illustrative description of the representative features of the Korean PRT system, which are expected to differentiate it from competitors as well as enlarge the potential for its extended application. The detailed specifications shown in fig. 1 are the target goals to be achieved in the Korean PRT development project (that is, at the end of the year 2016).

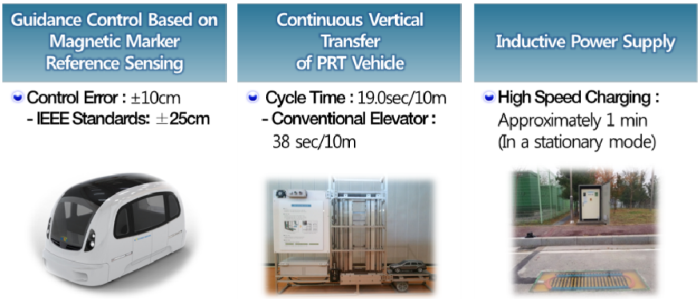


Figure 1: Description and requirements of the Korean PRT system and its key technologies.

3 Testbed-driven assessment

3.1 Design of road network for testbed-based evaluation

A pilot network was designed to assure the technical feasibility of a possible implementation scenario. Fig. 2 depicts a testbed road network implemented on the Korea Railroad Research Institute grounds. Its total length is approximately 650 m, and it has five shelters to provide real-time scheduling information using waiting and boarding passengers. In this network of roads, three loops were mainly considered to verify the control feasibility of the PRT test vehicle under various driving conditions, as well as the fleet operations of multiple PRT vehicles operating on a road network. In addition, these demonstration routes were designed and installed to assess the operational feasibility of various technical factors such as maneuvering stability at the minimum curvature radius of 6 m and slope of 33‰, remote calling of a vehicle for demand-responsive transport services, and high speed charging in a stationary mode at the station.

Figure 2: Demonstration routes designed on Korea Railroad Research Institute (KRRI) grounds for testbed-driven assessment.

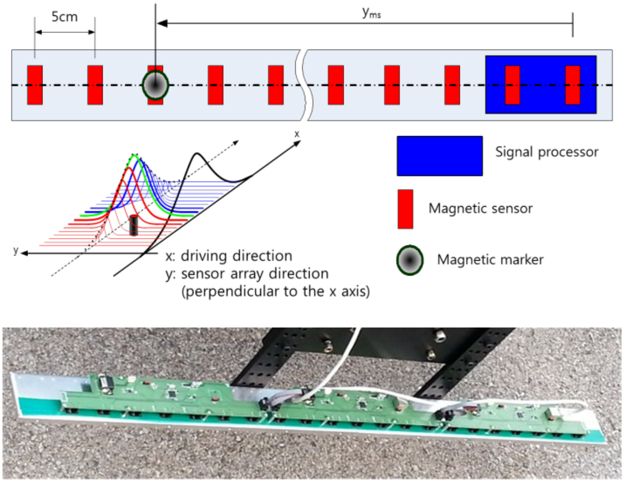
The testbed network was simply constructed based on the positioning of magnetic markers according to a trajectory design. The advantages of guidance control by means of magnetic marker reference sensing are its independence of weather conditions, low maintenance requirements, and simple construction on existing road infrastructure [6]. Fig. 3 shows one of the magnetic markers installed along the designed route. The interval between magnetic markers is determined depending on the expected operating speed of the vehicle, and control conditions, considering user comfort as well as the safety of the vehicle. The maximum operating speed of the Korean PRT system is 40 km/h, and the interval between magnets is approximately 3 cm for straight and 1 cm for curved roads, respectively.

Figure 3: Magnetic marker vertically buried in the ground. (Its diameter is approximately 15 mm; smartphone is for scale.)

3.2 Guidance control by magnetic marker reference sensing

The guidance control system is composed of two main components: magnetic markers (Fig. 3) which define center points along the path to be followed by the vehicle, and a Hall effect sensor module mounted on the vehicle for sensing the magnetic field emanating from the markers. The Vertical Magnetic Field (VMF) shown in fig. 4 was obtained by comparing the peak size of signals simultaneously and continuously detected by the Magnetic Sensing Ruler (MSR), since the peak signal corresponding to the actual position of a magnetic marker in a road is the strongest in the array of signals.

However, the variation in strength of continuous signals was not prominent, as shown in fig. 4, so additional signal processing of the measured signals is required to improve the robustness of the magnetic marker detection. Additionally, there was a discrepancy between the position referenced by magnetic marker and the actual vehicle position, caused by the time delay of signal processing, which is quite challenging and depends highly on the velocity of the vehicle as well as the number of samples. Thus, a complementary algorithm for an up-to-date estimation of the vehicle position is considered, to ensure the reliability and stability of guidance control.



(a)

(b)

Figure 4: Magnetic Sensing Ruler (MSR): (a) Schematic of the detection principle for magnetic markers and Vertical Magnetic Field (VMF), and a fabricated sensor module hooked up to the controller for signal processing; (b) the sensor module mounted on the vehicle.

Modular boards, each having a seven sensors array managed by a microcontroller, were connected next to each other. The completely assembled MSR controller board was integrated with three modular boards. The role of this board is to provide information on the vehicle position to aid routing, as well as to measure data obtained from the sensors to monitor the vehicle status, such as communicating the angle velocity of the wheel to the vehicle host computer. The communication to the vehicle host computer is carried out by a RS232 link as shown in fig. 5.

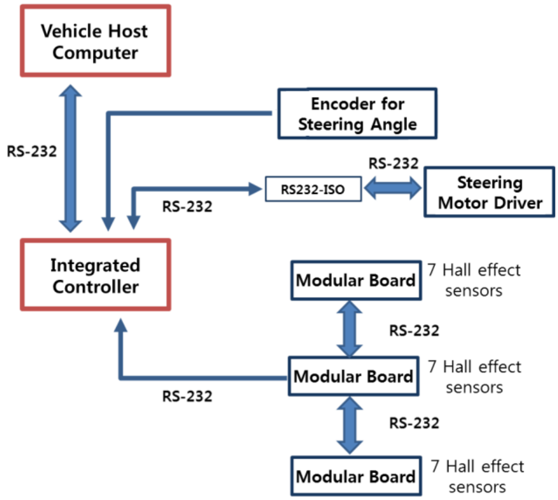


Figure 5: Electronic architecture of signal processing for autonomous guidance control using the MSR system.

The vehicle was automatically steered by mapping the detected marker position onto the geographic database of GPS logs of magnetic markers saved to the host computer. When users select their destination after boarding, the appropriate path is activated and displayed on the map (e.g., the red line shown in fig. 6). This touch-screen-friendly software enables users to request transportation as well as see the vehicle status. Real-time vehicle status information, such as its position and steering velocity, is displayed on the on-board computer as shown in fig. 6.

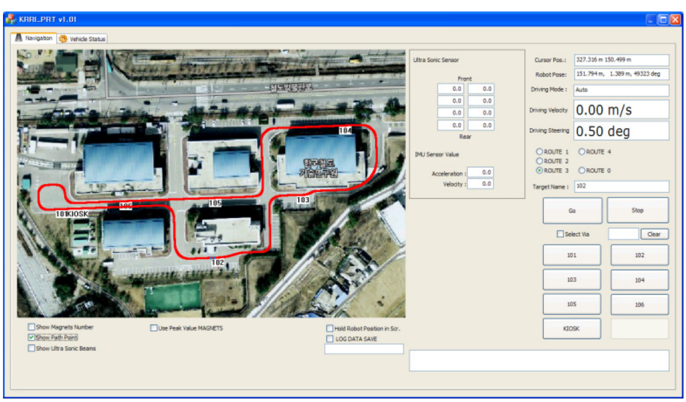


Figure 6: Screen shot of main control software executed in on-board computer for communication with passengers.

3.3 High speed charging using inductive power transfer

Initially, Li-ion batteries or supercapacitors were both considered for the primary energy storage devices for the Korean PRT vehicle. The advantage of the Li-ion battery is its capacity for long duration operation because of its high energy density; however, it is limited in use as a standard energy storage option due to its high initial cost relative to the life of the batteries. Most importantly, its weight and cost still needs to be reduced while delivering the same watts of power before its widespread introduction to the EV market.

On the other hand, the supercapacitor strong point is its ability to provide high power density in an instant. Most of all, the initial cost is not expensive, and it has a long life time compared to the Li-ion battery. While recent efforts to increase its power as well as energy density continue, it is still true that high volume is required to store high energy density. In this study, an evaluation of the Train Performance Simulation (TPS) analysis concluded that supercapacitors were more suitable for the Korean PRT system. That's because supercapacitors have the ability to deliver high power density for the short line distance between stations in a road network, and enable high speed charging by the Inductive Power Transfer System (IPTS) during the short time period while loading passengers. Table 1 represents the comparison of characteristics between the two different types of energy storage devices considered in this study.

Table 1: Comparison of TPS results and characteristics for Li-ion battery and ultra-capacitor [7].

Item	Values	
Energy required for one day (kWh)	63.2	
Li-ion battery (18650-15Q manufactured by Samsung SDI)	Charging time (hour)	3
	Weight (kg)	503
	Life time (cycle)	500
Supercapacitor (Series Connection of 4 modules (48 V, 166 F), manufactured by Nesscap)	Charging time (min)	1–2
	Weight (kg)	60
	Life time (cycle)	500,000–1 million

Fig. 7 shows the real picture of a Korean PRT station and wireless power supply infrastructure. The IPTS consists of a power inverter, power rails, and pick-up coil. The primary magnetic flux generated by Ritz cable buried in the ground, as shown in fig. 7, is used to induce the secondary magnetic flux flowing through the magnetic core installed at the bottom of the vehicle. Electromotive force caused by the change of the magnetic core flux is supplied to the energy storage device (i.e., supercapacitors) in the vehicle. The circuits of the IPTS fully resonate with the inverter switching frequency (e.g., 20 kHz) to deliver

Figure 7: Korean PRT station: The supercapacitor banks are charged by IPTS while in stationary mode at the station.

maximum power by reducing the leakage of the magnetic flux resulting from the air gap between circuits [4].

In this method, the system power efficiency highly depends on the precise control of the air gap, as well as any lateral misalignment between primary coil and pick-up coil while in the stationary condition. In the present investigation, 10 kW output power with 80.6% efficiency at the 10 cm air gap was achieved [7]. In addition, the lateral displacement error in vehicle control for a precise stop was approximately within the range of ±10 cm as mentioned in fig. 1. This value is below the maximum allowable lateral misalignment (i.e., roughly a quarter of the length of the primary core) [4]. The charging performance of supercapacitors using IPTS in the testbed experiment is presented in fig. 8.

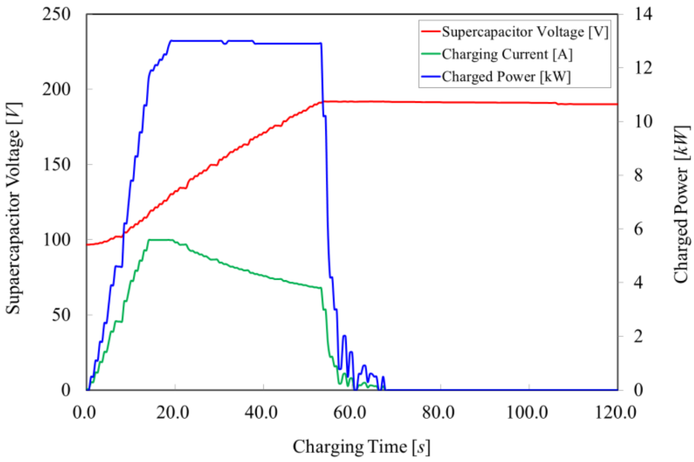


Figure 8: Characteristics of charging voltage and power of IPTS: supercapacitor banks are charged from 96 V to 192 V within approximately 1 minute.

4 Summary and conclusion

A possible implementation scenario of the Korean PRT system was described in this study. In addition, a testbed-based evaluation, considering the feasibility of technical implementation of the main technical features of the Korean PRT system was successfully conducted on a pilot road network on the KRRI grounds. A complete validation of target specifications has not been achieved yet, but this pilot experiment did provide some valuable information on future requirements that were not predicted in the preliminary planning study. Ultimately, this study contributes to reduction in risk in implementing the PRT system. Furthermore, it is expected to open extended applications and contribute to widespread perception of the PRT system as a highly accessible, user-responsive, environmentally friendly transport system, which offers a sustainable and economic solution.

Acknowledgement

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