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Quo Vadis PRT?

Review, Update and Outlook of Personal Rapid Transit in the Context of a Changing Urban Mobility Paradigm

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Abstract

Urban mobility as we know it is changing. On the one hand, challenges persist ranging from climate change, increasing urbanization and demographic change. On the other hand, recent technological advances enable novel approaches to mobility altogether. This paper investigates Personal Rapid Transit (PRT) as one such innovative mobility form in the context of the changing urban mobility paradigm. Due to its small, automatized capsules and dedicated guideways, a new level of convenience and efficiency can be achieved at least conceptually, which makes it worth analyzing in more detail. Conceived already 1954, only recently has the concept been proven feasible by successful pilot systems. In this thesis, key advantages and limitations of PRT are summarized and an update of recent developments is given. By means of expert interviews, current drivers and hurdles for the commercial diffusion of the technology are identified and evaluated. Furthermore it is argued that, given the changes to mobility, a window of opportunity exists where the automotive industry might be interested in PRT. Thus potential interactions between the innovative technology and the automotive industry are discussed. It is concluded that with the most recent steps of evolution, PRT could now be a highly competitive form of transit if certain barriers – mostly of political and economic nature – are overcome. For this a champion is needed, which the automotive industry could provide. Thereby, a range of mutual benefits could be possible for both industries.

Keywords: Personal Rapid Transit, PRT, innovative mobility, sustainable transport, sustainable transit, automotive

Executive Summary

Background

The 20th century urban mobility paradigm is challenged by factors such as Climate Change, ongoing urbanization, demographic change and changes in mobility patterns. Furthermore, technological developments such as progress in information and communication technology as well as vehicle automation change the way such challenges are approached.

One innovative mobility concept that, as its proponents claim, could be an appropriate solution to these challenges, is Personal Rapid Transit (PRT). It is a system of automated, electric, small vehicles (so-called 'pods') for 2-6 passengers that run on segregated guideways. Stations are located off the main line, providing for non-stop journeys and thus, for urban transport, very high average speeds. Theoretical advantages of PRT include higher energy efficiency per passenger kilometer and shorter total trip times than a comparable tram system, while having lower capital costs than the same and allowing for profitable operation. Being automated and silent, PRT can run 24/7 and on-demand, with no or very low wait times. It boasts extremely high rates of safety and reliability and can offer privacy. Social benefit-cost analyses are consistently favorable of PRT due to expected time savings and low costs for operation. These advantages have been confirmed both in practical pilot projects and several extensive EU funded research studies.

Research motivation, Research Questions and methodology

Since 2010, first PRT systems have been built. It is however unclear what the current state of the technology's industry is. Also, although substantial research has been conducted on PRT, much of that literature is several years old. In order to have a realistic assessment of the concept, an up-to-date image of it is important. Of particular relevance is the question what the current drivers and hurdles to the commercialization of PRT are. Moreover, PRT offers a service somewhere between private and public mobility. As the automotive industry is currently facing times of dramatic changes, it is hypothesized that a window of opportunity exists where interactions between PRT and the automotive industry could be mutually beneficial. Therefore the automotive industry provides a promising focal point for further analysis of the potentials of PRT. Since this thesis project was performed in cooperation with the Volkswagen Group Department of Corporate Foresight, this perspective is included in the research approach.

Consequently, The Research Questions (RQs) answered in this thesis are:

RQ1: What is the current state of PRT?

RQ2: What are current key drivers and hurdles in the commercialization of PRT?

RQ3: What are possible interactions between PRT and the automotive industry?

In order to answer these questions, data was collected by means of literature review, online search and semi-structured expert interviews. Each RQ is answered by its distinct methodology. RQ1 is mostly descriptive and primarily draws on literature review and online sources. After a background on PRT is given and its advantages and limitations are outlined, the status quo is drawn. The existing systems, recent activities and a market forecast are presented.

RQ2 is answered chiefly by means of the expert interviews. The analysis follows the PESTLE framework by which the technology is assessed according to political, economic, socio-cultural, technological, legal and environmental factors. This is done for the drivers and hurdles separately. The qualitative analysis tool Maxqda was used for structuring and quantitatively analyzing the interviews. The results of this part guide and validate the qualitative analysis which forms the core of the answer to RQ2. Synthesizing the results from the analysis, the current state of PRT is assessed.

Lastly, given its hypothetical nature, RQ3 is answered by means of a critical discussion.

Key findings

RQ1

- PRT has existed since 1954 as a concept but has only now become technically feasible. It is a mobility solution that can offer superior service to passengers, is environmentally friendly, comparatively cheap to install and may be profitable to operate. It is best suited to small to medium sized cities (up to 200 000 inhabitants) or special applications such as airports, malls and corporate and university campuses.
- Globally, three 'true' PRT systems exist that went live since 2010. Otherwise, there are currently limited activities regarding PRT. The existing system suppliers are comparatively small and offer technically distinct system designs. A lack of industry standards and streamlined production increases planning complexity and costs.
- Key advantages of PRT claimed by its proponents hold true in reality. However, due to the absence of a full-scale application in an urban setting, there are still uncertainties regarding its carrying capacity and reliability in a network (where it should have its largest advantage over conventional transit).

RQ2

- The strongest driver for PRT is that most unique capabilities inherent to the concept are proven to work. PRT is an environmentally friendly technology with large customer benefits and good potential to address numerous policy objectives in a cost-effective fashion. Moreover, the fit with current public and political discourse and low legal barriers to implementation compared to other forms of automated mobility make it well suitable to address urban mobility challenges.
- However, a vicious cycle of hurdles is strongly limiting its implementation. These include the relatively high capital costs needed to set up a demonstrator; a lack of business models for the infrastructure; visual intrusion; high levels of complexity and uncertainty in the planning process; and difficulties related to public procurement. The lack of knowledge of third parties and the dependence on local political cycles aggravate these issues in an urban context.
- Most of these hurdles relate to the PRT infrastructure. While it allows the concept to offer transit service of a unique quality, it is therefore a hurdle by itself (see Figure I).

- Particularly the absence of a full-scale demonstrator that proves the functionality of PRT in a network and reduces uncertainties regarding its carrying capacity is problematic (see Figure II).

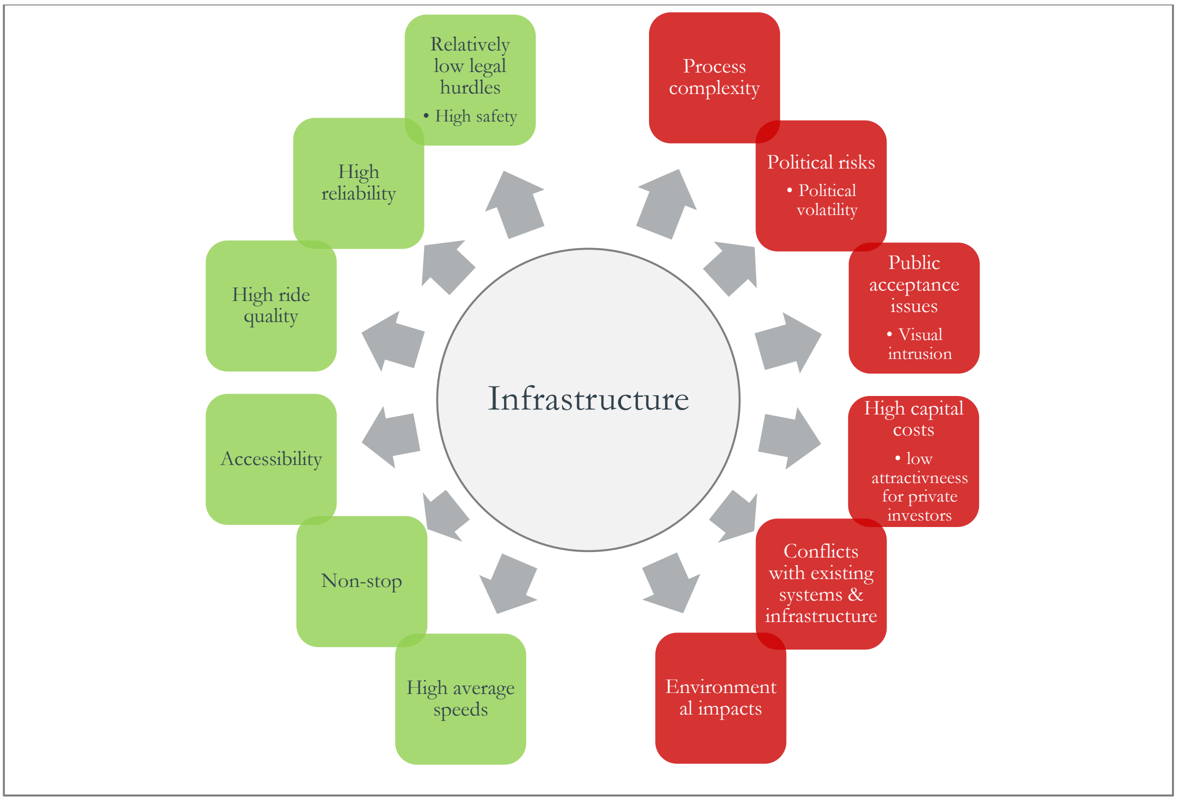

Figure I. Pros and Cons of the PRT infrastructure

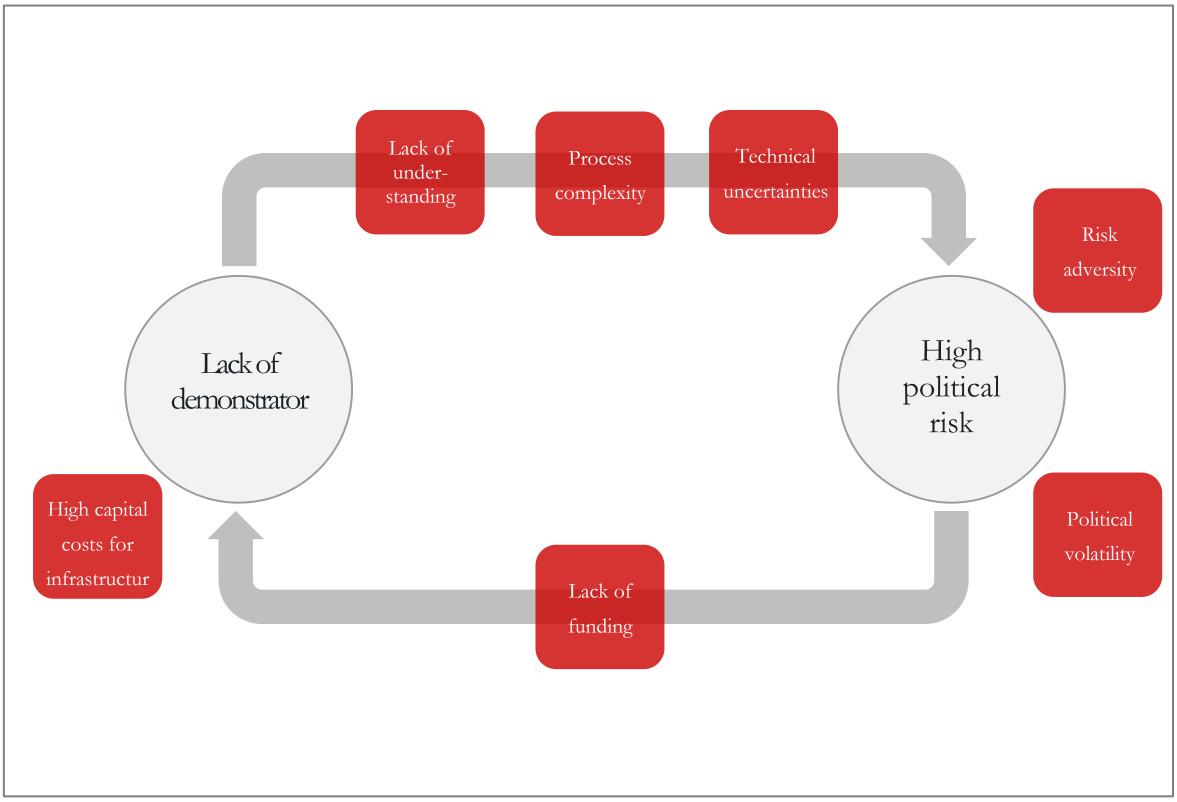

Figure II. Vicious cycle of the lack of full-scale demonstrators

- These hurdles are not, however, insurmountable.
  - A **champion** with sufficient political and financial endowment could help PRT overcome the core hurdles identified by realizing a larger, network-sized system ideally in an urban setting. This would break the vicious cycle related to the lack of suitable demonstrators.
  - It would be advantageous for PRT to evolve to be **less dependent on its guideway** to circumvent the difficulties associated with it if wherever the infrastructure is not adding a compelling advantage.

RQ3

- PRT may be an opportunity for the automotive industry as a complementary strategy to road vehicle automation in order to react to current challenges to the industry. PRT suits the current trend for vehicle automation, could enhance the image of a car company, and provide new business opportunities. Thereby it could be a way for the automotive industry to react to the trend of the 'car-free-city'.
- A range of mutually beneficial interactions are thinkable between PRT and the automotive industry. Especially promising are
  - A Dual-Use PRT system where small city vehicles can co-use the light PRT infrastructure
  - Integrating PRT in a mobility hub such as a MicroCity
  - PRT evolving to being able to leave its guideways
- Implementing any of these options faces engineering challenges that are not trivial but can be solved with the appropriate commitment.

- Business models of PRT and the automotive industry are currently different but may become more similar in the future in an 'automated road vehicle' scenario.

In conclusion, this thesis finds that PRT is an intriguing technology whose time has come – if it receives appropriate support to overcome key hurdles that keep it from scaling. An actor from the automotive industry could be the champion providing this needed support. Some possible interactions between PRT and the automotive industry are discussed, arguing that there are many potential synergies that could make PRT a viable option to consider. Then, challenges to urban mobility could be addressed effectively and potentially profitably.

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Abbreviations

APM	Automated People Mover
ATN	Automated transit network
ATRA	Advanced Transit Association
ATS	Automated Transport Systems
ATS ltd.	Advanced Transport Systems ltd.
BOOT	Build, own, operate transfer project financing scheme
BRIC	Country group Brazil, Russia, India, China
C2X	Car-to-Infrastructure /Car-to-Car communication
CO2	Carbon dioxide
CSR	Corporate social responsibility
CTS	Cybernetic Transport System / cybercar
EDICT	Evaluation and Demonstration of Innovative City Transport
EU	European Union
FRT	Freight Rapid Transit
GDP	Gross domestic product
GHG	Greenhouse gases
GRT	Group Rapid Transit
HMRI	Her Majesty's Rail Inspectorate
ICT	Information and communication technology
ITS	Intelligent transport solutions
km/h	Kilometers per hour
LCA	Life cycle analysis
LRT	Light rail transit / Tram
LUTZ	Low-carbon urban transport zone project
MJ	Mega joule
OECD	Organization for Economic Co-operation and Development
OLED	Organic Light Emitting Diodes
P&R	Park & Ride
PESTLE	Political, Economic, Socio-cultural, Technological, Legal, Environmental analysis heuristic
pkm	Passenger kilometer
pphpd	People per hour per direction
PPP	Public-private partnership
PRT	Personal Rapid Transit
PT	Public transport / transit
R&D	Research and development
RQ	Research question
RTA	Chicago Regional Transportation Authority
SCOT	Social Construction of Technology
UITP	International Association of Public Transport
UN	United Nations
USA / U.S.	United States of America
VW AG	Volkswagen Aktiengesellschaft / Volkswagen Group

"Over the next few years, [the automotive] industry will face one of the greatest upheavals since the invention of the automobile. People's mobility expectations are undergoing a fundamental transformation. […] The automobile industry must not bury its head in the sand but must welcome these developments and take them into account in its long-term strategies."

Martin Winterkorn, CEO Volkswagen AG, March 2014

1. Introduction

1.1 Problem definition

Globally, our mobility paradigm is challenged. Particularly urban mobility is reaching a tipping point. As a major emitter to greenhouse gases (GHG), transport must be 'de-carbonized' substantially to help avoid dramatic climate change. Urban transport contributes substantially to overall transport GHG emissions, making it a focal point for improvements. Moreover, already today "existing [urban] mobility systems are close to breakdown" (Arthur D. Little & UITP, 2014, p. p6). Driven by mega-trends like urbanization, demographic change and economic growth in developing countries, these issues are set to become bigger. Gridlock, traffic deaths and other negative externalities – social, environmental and economic – are the result. At the same time, the progress in technologies, particularly in sensor technology and information and communications technology (ICT), allows completely new forms of mobility that were not conceivable only a few decades ago. This opens new options for public authorities and system providers but also creates a new demand by customers and requires new regulations. This mix of problems and opportunities increasingly challenges the traditional 20^{th} century mobility paradigm, which was heavily based on individual car ownership, complemented by public transit.

Facing these challenges, especially in industrialized countries private and public actors of different levels are taking various measures. Particularly in the European Union (EU), activity has been high to this regard in the last decade. On the one hand, many public authorities (cities, national governments, etc.) want to reduce car travel in cities, inciting a shift to more efficient modes of transport. Sharing concepts are booming and cities like Amsterdam, Copenhagen and Hamburg even restructure much of their road infrastructure for biking and walking. National governments are supporting efficient transportation through legislation and government programs. On a supranational level, in the context of the strategy on the urban environment the EU is active among others by supporting research into Intelligent Transport Solutions (ITS) and Automated Transport Systems (ATS) and is working to adjust the legislative framework. Private actors are heavily engaged, too – ranging from start-ups to industrial initiatives. One of them, the automotive industry is working to reposition individual mobility in the emerging context for example by intensifying research on vehicle automation. It promises increased fuel efficiency, better use of space and improved safety – not to speak of new ways of brand differentiation. Moreover, the industry is exploring options beyond the vehicle itself, ranging from integrated mobility services to Vehicle-to-Vehicle and -Infrastructure communication to novel cross-industry cooperations.

At the same time, innovative urban mobility solutions are being developed that not only claim to help solve the growing urban mobility challenges but may also close the divide between public and private transport. One of these is Personal Rapid Transit (PRT), a system of automated, electric, small capsules (sometimes called 'pods' or 'pod-cars') for 2 – 6 passengers that run on segregated guideways. Stations are set off the main track, which allows capsules to bypass all stations except its destination. This creates the opportunity for non-stop journeys and thus, for urban transport, very high average speeds. In theory, advantages of PRT include higher energy efficiency per passenger-kilometer and higher travel speeds than other modes of transit, while having lower capital costs than a comparable tram system by a factor of 2 to 3 and allowing for profitable operation. Social benefit-cost analyses are consistently favorable of PRT due to passenger time savings, low costs for operation and high efficiency. It has been evaluated as more convenient than conventional modes of transit. Moreover, the small, silent vehicles and light infrastructure create new design opportunities for this transport system. These advantages have been confirmed both in practical pilot projects and extensive EU funded research studies (notably EDICT, 2005 and CityMobil, 2011). These many potential advantages make PRT an intriguing technology worth studying, which is why it will be the topic of this thesis.

While the concept of PRT has been discussed since the 1960's and countless systems have been drafted for cities around the world, larger-scale PRT applications have not been built yet. Previously, key hurdles for PRT implementation identified in the literature were not primarily technical but relate to issues of politics, public acceptance and system certification. Much of the PRT literature is several years old though: the last large scientific study of PRT was published in 2011, while the first true PRT systems commenced operation in 2010 and 2011. Since then a comprehensive picture of the current state of PRT is lacking, while progress on technologies relevant to PRT (particularly ICT and automation technology) has been rapid. This makes it difficult for stakeholders to evaluate the technology – which increases perceived risks and therefore reduces the likeliness of adoption. This justifies both giving an update on the status quo of PRT and investigating the current drivers and hurdles of PRT.

Conceptually, PRT combines elements of both individual and public transport and may be dubbed an intermediary between both. Since solving mobility challenges outlined above will require an integrated approach of both public and private actors applying both individual and public transportation combined with a suitable policy mix, this offers an interesting proposition: If car manufacturers could be interested in becoming engaged in supplying PRT-like systems, incentives could be aligned and more integrated mobility solutions might be found. The tire-based design of two currently piloted systems make PRT appear technologically close to home for automotive companies. Because these are currently interested in new approaches for urban mobility, there seems to be a window of opportunity for innovative mobility systems in this industry. This raises the questions how PRT may impact the automotive industry and whether there could be an opportunity for mutually beneficial interactions between the two, offering not only a possible way forward for the automotive industry but also speeding up the adaptation of innovative mobility concepts. Therefore the automotive industry provides a promising focal point for further analysis of the potentials of PRT. Since this thesis project was performed in cooperation with the Volkswagen Group Department of Corporate Foresight, this perspective is included in the research approach.

The identified research gaps lead to the following research objectives: The first research objective of this thesis is to draw the state of the art of PRT. The second research objective is then to identify the current drivers and hurdles for the implementation of PRT systems from literature and through expert opinions. The third objective of the thesis is to investigate what interactions could be possible between PRT and the automotive industry.

The corresponding Research Questions (RQs) to be answered are:

RQ1: What is the current state of PRT?

RQ2: What are current key drivers and hurdles in the commercialization of PRT?

RQ3: What are possible interactions between PRT and the automotive industry?

1.2 Methodology

1.2.1 Data needs and means of data collection

The initial data collection involved a literature review of academic articles, research projects and grey literature, as well as internet searches for the most up-to-date news on PRT globally. Herein, the academic literature formed the basis for the definition and description of PRT, its conceptual and confirmed potentials and limitations (RQ1), as well as previously identified drivers and hurdles for the technology's commercialization (RQ2). Grey literature – i.e. project descriptions, PRT company reports, consultancy work, etc. – complemented the academic literature not only by giving more up-to-date evaluations (RQ1) of existing projects but also by giving insights into the experiences with project processes of previous PRT studies (RQ2). Six larger studies and several dozen other papers on PRT were used for the writing of this thesis.

Expert interviews constitute the core of the thesis and contributed to data collection in several ways. Firstly, interviewing experts directly engaged with the technology made it possible to give an update of PRT beyond publicly accessible material (RQ1). Secondly, they allowed a review and expansion of the findings on drivers and hurdles from the literature (RQ2). Thirdly, the experts' evaluations were a key source of information for the potential of PRT in terms of market growth and its impacts both on sustainable urban mobility and the automotive industry (RQ3).

The expert interviews took the form of semi-structured interviews and were conducted following guiding questions related to the research questions (see appendices A and B). The guiding questions were peer reviewed and pre-tested in a pilot interview to ensure academic quality and relevance to the research questions. The questions catalogue was adapted with two questions for the Volkswagen experts to account for the different perspective on a potential involvement of Volkswagen and the automotive industry, and to inquire about relevant internal competencies regarding PRT where applicable. The guiding questions can be found in Appendices A and B.

The selection of experts followed different stakeholder groups identified in the literature and was achieved primarily through referral sampling. A wide cross-section of relevant stakeholders was achieved, including representatives from academic research, the European Commission, PRT consultants, a project development company, an airport, city authority and the automotive industry. Most interviewed experts hold senior positions in their respective field, giving particularly valuable insights into the wider context of urban and automotive mobility. Unfortunately it was not possible to establish contact with a PRT company in time to conduct an interview for this thesis. A list of the interviewees is given in ***Table 1***. In total, 17 interviews were conducted, five of which were short due to time constraints. The others lasted between 45 minutes and one hour without anything forcing their end. The Interviewees were all very open to answering the questions and were actively engaged in discussion.

Table 1. List of interviewees

Position	Name	Type of expert	Experience with PRT
Lead evaluator, CityMobil; coordinator, CityMobil2	Adriano Alessandrini	Academic	Yes
Associate director, Arup UK; Board Member ATRA	Austin Smith	Engineering consultant; PRT consultant	Yes
Senior engineer, Arup UK	David Watkins	Engineering consultant; PRT consultant	Yes
Senior consultant, WSP	GöranTegnér	Consultant; PRT consultant	Yes
Prof. em., KTH; Director LogistikCentrum	Ingmar Andreasson	Academic; PRT consultant	Yes
Head of Automotive & Transportation, Frost & Sullivan	Martyn Briggs	Mobility consultant	Yes
Senior consultant, Frost & Sullivan; Ultra PRT	Nick Ford	Mobility consultant; PRT consultant	Yes
Head of Urban Mobility, DG Research, European Commission	Patrick Mercier-Handisyght	European Commission	Yes
Director Sales & Marketing, Scania	Anonymous	Automotive / Bus	Yes
Senior manager, Research Support Office, Scania	Anonymous	Automotive / Bus	Yes
Managing director, Stuttgart Airport	Walter Schoefer	Airport	No
Researcher, Institute for Transportation Design, Braunschweig	Thomas Sauter-Servaes	Academic	No
Colliers International	Philipp Nothdurft	Real estate industry	No
Head of “New Mobility”, Wolfsburg AG, Germany	Gerrit Schrödel	Transport planning	No
Head of team, Volkswagen Group Corporate Research	Anonymous	Automotive	No
Head of team, Volkswagen Group Corporate Research	Anonymous	Automotive	No
Head of team, Volkswagen Group External Relations	Anonymous	Automotive	No

Every expert was offered anonymization of his[1] contribution. Most experts permitted the use of their name. Where possible, interviews were recorded in audio. In these cases, the interviewees were explicitly asked for permission prior to the interview. Each interviewee was sent the summarized transcript of his interview for confirmation before it was used, ensuring correctness of the data.

The special role of internal experts of the Volkswagen Group is worth mentioning. Writing the thesis in cooperation with the department of Corporate Foresight of the Volkswagen Group allowed the author to have access to a range of highly experienced personnel within the company. While it became clear that these had – as expected – no personal or professional experience with PRT, their contributions to the in-depth conceptual assessment of the technology and particularly its relevance for the automotive industry provided a rare perspective for the research. The interviews of the experts are personal statements and do not represent the official opinion of Volkswagen. According to company policy on data protection, they remain anonymous and their interviews were not recorded. To avoid conflicts of confidentiality, no proprietary information of Volkswagen was used in the context of this thesis.

1.2.2 Method of analysis

Different methods of analysis are employed for each research question. RQ1 is primarily descriptive, aiming to give an up-to-date image of the state of PRT.

The analysis for RQ2 follows the PESTLE framework, according to which the drivers and hurdles of PRT were structured according to the following categories: Political, Economic, Socio-cultural, Technological, Legal, and Ecological. This simple heuristic allows for a structured overview and analysis of a technology in its particular context and is widely applied for example in market evaluations. A PESTLE analysis of PRT was previously conducted for PRT in a market study by Frost & Sullivan (2012). Furthermore it was tested whether any of the main components of PRT plays a particularly important role in relation to the identified drivers and hurdles.

To clarify which drivers and hurdles were named by which experts, a matrix was initially created relating each expert to the drivers and hurdles he named and grouping the experts according to their background to see whether (unconscious) biases or hidden agendas would influence the answers of the experts. Given the large amount of data collected, the qualitative data analysis software Maxqda was used to structure the replies. The software allowed the author to a) structure the transcripts for ease of analysis, b) identify which drivers and hurdles were named most often and by which expert, c) get an overview of which PESTLE categories related to each other and to which physical component of PRT, and d) visualize the data.

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[1] All experts happened to be male, so that when referring to the experts, the male form will be used in the paper from hereon.

While the analysis with Maxqda formed the starting point for the analysis by giving an overview and structure to the interview results, the critical qualitative analysis goes beyond this by discussing the complex interactions between the single aspects. For example, the need for infrastructure was often identified as a key hurdle by interviewees, not in and of itself but because it creates high costs, path dependency, demands careful local planning and increases the political risk of building a PRT system. In the analysis, the qualitative evaluation of the factors and some key concerns voiced by the experts are highlighted and the overall implications for PRT and its potential discussed.

Last but not least, Q3 is answered by means of a critical discussion drawing on the results of the analysis and the expert opinions. A full critical analysis is not possible in the context of this thesis due to several reasons: Firstly, due to the nascent state of the PRT market, the rapid development of technology and the inherent volatility of future developments, definite answers to RQ3 are not possible. Secondly, more comprehensive information would be needed to perform a full market analysis. Thirdly, strategic information of both the automotive industry and PRT companies is confidential and thus not available for the writing of this thesis. Nonetheless the discussion of Q3 adds value by pointing to some relevant aspects of the potential interaction between the automotive industry and PRT.

1.3 Scope and limitations

This thesis considers PRT as a general concept and technology, therefore taking a fundamentally global view. However, the vast majority of existing literature comes from the USA and the EU and the most recent experiences as well as all current system suppliers are European. Therefore the focus of the analysis rests on the European context. Transferring the findings, particularly those related to politics and customer acceptance, to the context of other countries and cultures should be done with caution.

The analytical focus of this paper is wide, giving a review of the technology and issues in its application, as well as implications for one industry. It does not aim to be a technical paper, nor is a thorough political analysis or full-scale market evaluation. Rather, the aim of this paper is to synthesize previous experiences with PRT and point to important aspects that could influence the success or failure of the technology in the future.

Although considerable work has been done on PRT in the past, only parts of the literature were accessible for writing this thesis. Moreover, due to the large variety of systems qualifying as PRT – or mistakably being labeled as such – and the changes in conditions (technological, political, legal, etc.) over time, the transferability of many of the findings have to be done with care.

Further limitations are methodological: Basing a substantial part of the analysis on expert interviews inherently limits the transferability of the findings in several ways. First, the range of experts interviewed does not fully represent the full breadth of potential relevant stakeholders to a PRT project. For example, neither politicians nor PRT companies were interviewed directly. Therefore some valuable perspectives may be absent from the analysis. However, the remaining selection of experts somewhat ameliorated this issue: For example, Mr. Mercier-Handisyde from the European Commission Directorate General Research certainly has an overview of the political process regarding PRT projects. By the same token, the consultants from Arup have long-standing experience in close cooperation with city governments. The limitation may therefore be less significant. Second, the sampling of experts partly followed convenience- and referral sampling. This may introduce a sampling bias. Third, all interviewees are European, even though most have extensive international working experience. This limits the plurality of perspectives, especially since none of the interviewees was particularly involved and knowledgeable about the developments of PRT in emerging markets like India, China or Brazil. Fourth, like any interview based research, the experts may have hidden agendas or biases, can which influence their answers. It is also clear that although based on vast experience in the field, the export opinions remain subjective. As noted in the methodology section above, attempts were made to account for these limitations. Moreover, the intersubjective evaluation of a range of experts addresses these limitations to an extent and offers interesting insights not readily available from literature.

It became clear during the interviews that the experts' knowledge and understanding of PRT is difficult to assess. Even if most aspects of PRT are clear to the interviewees, some aspects of their understanding may substantially alter their evaluation of PRT, sometimes making their assessment unrealistic – also confirming one restraining factor previously identified in the literature. This is particularly true for those experts who had no previous experience with PRT. Moreover, as no full-scale commercial application exists to fully prove the concept, some evaluation by the author as well as the experts had to be done on the basis of analogy or extrapolation – which is a problem inherent to all innovative technologies. In the analysis, in order to reduce the complexity arising from the large amount of relevant factors and their interactions, some level of aggregation had to be done by the author based on informed judgment calls.

Importantly, company specific results should not be generalized to entire industry, as other car manufacturers have a different innovation culture or market positioning that could lead to different results.

1.4 Audience

This thesis was written for academic review for the fulfilment of the Master of Science in Environmental Management and Policy at the International Institute for Industrial Environmental Economics (IIIEE) at Lund University. It is also intended for the kind consideration of the Volkswagen Group Department of Corporate Foresight, which supported the process.

The intended audience of this thesis includes firstly policy makers and local authorities who are curious about PRT as an option for a sustainable urban transport policy or mobility system. Secondly, it will be relevant for the automotive industry and other businesses which are looking at PRT as a potential new business opportunity or competing technology. Thirdly, it is directed at academics in the fields of urban and transport planning as well as ATS.

1.5 Expose

The paper will proceed as follows: Chapter 2 gives the context of the currently changing urban mobility paradigm, thereby arguing why alternative solutions like PRT may be relevant and suitable. Next, Chapter 3 introduces the concept of PRT and its history, outlines pros and cons and identifies suitable applications. Moreover, answering RQ1 a status update and a market analysis are presented based on literature and expert interviews. Chapter 4 turns to address RQ2: lessons learned from past PRT projects are summarized and the current drivers & hurdles are analyzed. The chapter closes with a synthesis of the results, drawing some conclusions on the current situation and future potential of PRT. Chapter 5 discusses potential future interactions between PRT and the automotive industry, particularly in the context of vehicle automation (RQ3). The findings and the research process are discussed in Chapter 6. Concluding, Chapter 7 summarizes reflects on the Research Questions and proposes fields of future research.

2. Context: Challenges to the (Urban) Mobility Paradigm

Throughout the 20th century, individual mobility has increased dramatically in industrialized countries along with economic growth, largely by means of the car and, particularly in cities, through public transport. Nowadays, people in developed countries enjoy the highest level of mobility of all times, and many developing countries are catching up quickly (WBCSD, 2004). However, this development brings with it its own challenges, which include the need to reduce harmful emissions, GHG emissions, traffic deaths and congestion, as well as maintain and improve mobility, particularly in poorer countries and for the ageing society (ibid.).

In all of these points, urban mobility is particularly relevant: On the one hand, problems are most explicit here. On the other, cities offer the greatest potential and leverage to create solutions. In the following section, core challenges to urban mobility are presented.

2.1 Climate Change

With the publication of the 5th assessment report by the IPCC from 2013 to 2014, it is corroborated better than ever that man-made climate change is real and will with high probability lead to dramatic and runaway effects world-wide if we do not substantially decrease our GHG emissions (IPCC, 2013). Effects – many of which have already started to be observed in the last decades across the globe – include more extreme weather patterns, rising sea levels and impacts on highly relevant environmental conditions like the distribution of diseases, drinking water availability and food production (IPCC, 2014). Like the Third U.S. National Climate Assessment Report, released May 6 2014, has recently highlighted, the impacts of climate change on human life and economic prosperity will be devastating and first effects like increased wild fires and heavy rain patterns are already occurring today at great costs to the economy, humans and nature (Global Change Research Program, 2014).

Globally, transportation accounts for at least 27% of final energy use and to 14% of all man-made GHG emissions (IPCC, 2013). Therefore, reducing GHG emissions from transport is of high importance to mitigate climate change. However, the baseline CO_2 emissions of transport are not decreasing – quite the opposite, they are projected to more or less double by 2050 (IPCC, 2014). Since of all transport-related GHG emissions currently at least 40% are caused by transportation in urban areas, urban transport is a focal point for decreasing GHG emissions in transport (European Commission, 2014; IPCC, 2013).

2.2 Urbanization

The fact that urbanization is proceeding further emphasizes this focus. By 2050, 66% of the global population will live in cities, up from 54% today. While much of this increase will take place in developing countries, in the EU-27, already today over 70% live in urban areas. Since 85% of all value added takes place in cities and vital function like government and commerce take place here, their smooth functioning is of great importance to any economy (United Nations, 2014). However, besides contributing to GHG emissions of cities, the increase in urban mobility also has other downsides: For example, the social costs of congestion, accidents and air pollution are estimated at € 1 billion or 1% of the EU's GDP annually – globally, these costs have even been estimated to a dramatic € 823 billion per year in 2012 (European Commission, 2014; Arthur D. Little, 2011). Still, driven by population growth and increases in GDP per capita, the demand for personal mobility is projected to increase by another 30% in OECD countries and between 250 and 350% in non-OECD countries by 2050 (OECD ITF, 2012); as a result, some reports expect the number of vehicles globally to double to 2 billion by the end of the decade and increase to up to 3 billion throughout the century (Navigant Research, 2013).

At the same time, only few cities are well prepared to provide sustainable mobility. Space is a key constraint – congestion becomes the norm and parking increasingly expensive. While suitable policies, business models and technologies are available, their application remains locally specific and difficult, preventing scaling them to address the challenges (Arthur D.Little & UITP, 2014). Even though the modal share of cars has stagnated in European cities and is projected to decrease by 7% until 2025 (European Commission, 2013), pressure on the urban mobility systems is rising here as well, leading to high costs. The European Commission estimates them to over € 1.5 trillion until 2030 for mobility measures including the expansion of infrastructure and mobility services, but also maintaining ageing infrastructure (European Commission, 2011). Globally, it has been estimated that at least $ 4 billion of infrastructure investments will be necessary globally until 2020 alone (WEF, 2013). It is therefore clear that urbanization not only creates opportunities but also poses formidable challenges for public and private actors. Effective, scalable and economic solutions are urgently needed.

2.3 Demographic change

Along with environmental problems and urbanization, demographic change deeply transforms the needs for urban mobility worldwide. The world is getting crowded: The global population is projected to reach almost 10 billion people by 2050 – 95% of that growth taking place in developing countries (United Nations, 2014). Of the global population, 2 billion will be 60 years or older; 32% of them will live in currently industrialized countries. The population older than 80 is expected to more than double. Particularly in the already developed countries, population ageing is becoming visible and requires attention (BMZ, 2013). Mobility needs for this demographic segment will have to be considered much more. Neither traditional public transit nor current car designs are suitable to the elderly's needs and will have to be adapted substantially. While the automation of cars is one way to support older drivers in individual mobility, public transit faces additional issues like last-mile connectivity, accessibility, complexity reduction and convenience that need to be considered to provide mobility to the growing proportion of older people (International Transport Forum, 2011).

2.4 Changing mobility patterns & culture

Over the last decade or so, it was possible to observe a deceleration of demand for passenger travel in developed countries. While in previous decades a close coupling between GDP growth and travel demand existed, this link seems to be weakening. Particularly car travel volumes have stalled or even receded in many developed countries while GDP continued to rise (OECD ITF, 2012). There is no one single factor explaining this. While it is well established that the ageing of the population and cohort effects play a significant role as the market of mobile people is starting to shrink in these countries, other factors are more complex. For example, the rapid developments in ICT have started to affect mobility options and -behavior, but its ultimate impacts are still uncertain. Mobility choices have started to change, showing a stronger individualization and diversification of mobility users. This trend is owed in parts to an increase in available mobility options particularly in urban areas, partly as conscious lifestyle choices for sustainability, and partly due to budgetary constraints. Policy interventions are important: Particularly in urban areas but also on state and the supranational level, activities to incite a shift to more environmentally friendly modes of transport can be observed to have an effect (ibid.).

These developments are not universal but differ between countries, regions and cities and the various factors have different weight in each. It is important to distinguish between developed countries on the one hand and emerging economies on the other: While globally a 32% increase in individual mobility is projected until 2025, 83% of this will take place in BRIC states (Brazil, Russia, India and China) (Roland Berger, 2011). Still, while for now developing markets continue to experience strong growth in mobility, particularly individual mobility, the challenges these countries face like urban grid-lock and health effects are expected to prompt more drastic policy changes soon (OECD ITF, 2012). Costs for individual mobility have been rising in many countries due to rising costs for fuel, licenses and insurance. Some are concerned that the policy push for more energy efficient, particularly battery electric vehicles, exacerbates vehicle costs, which could become a question of equity. At the same time, the additional demand for public transit brings these systems to their capacity limits – thus the assessment by the UITP quoted in the first paragraph of this paper.

Possibly driven by the rising prevalence of environmental problems globally, the trend towards more ‘sustainable’ consumption is ongoing and having the image of a responsible company is increasingly relevant for success. For example it has been found that 40% of companies’ reputation is influenced through corporate social responsibility (CSR). Good environmental and social performance has been linked to attractiveness for employees – for 88% of recently graduated employees, the so-called ‘Generation Y’, strong CSR values are of high importance when choosing their employer –, shareholder value and profitability (Mohin, 2012). Particularly in difficult markets, sustainability is now a differentiating factor (EY, 2014). This is also impacting the mobility market. In a 2011 Gallup survey, 60% answered they would accept lower speeds, size and range of cars for better fuel consumption, 50% a higher price, and 65% would combine different transport modes if better intermodal integration existed (Gallup, 2011). How large the willingness to pay is in realty remains a matter of empirical and theoretical research. Particularly relevant to the automotive industry is though that young people are losing interest in owning a car and the percentage of owners of drivers licenses is decreasing in the western countries (79% in 2011 vs. 92% in 1983 in the USA) (Roland Berger, 2011; Bloomberg Businessweek, 2013).

Conversely, novel and especially intermodal types of mobility are emerging in urban areas particularly in OECD countries. While still only a fraction of the market, car sharing is growing rapidly: by 2020, 15 million users are expected in the EU alone – up from 0,7 million in 2011 (Frost & Sullivan, 2012a). Since each car sharing vehicle replaces several cars – estimations range between 3 and around 30 depending on the context – and car sharing users drive 31% less than car owners, the impacts on mobility patterns in urban areas are expected to become significant in the long run (Frost & Sullivan, 2010). Intermodal platforms are emerging and spreading fast. Ad-hoc intermodal journey planning is expected to become the standard in cities, redefining not only mobility usage but the entire market and business models in urban mobility.

Overall, the car loses its position as the one dominant mode of transport as convenient and efficient mobility becomes more important for city dwellers (F21, 2013). In effect, the automotive companies themselves have started preparing to become integrated mobility providers instead of pure car manufacturers (KPMG, 2014) – A fundamental paradigm shift, whereby previously unknown technologies, partnerships and business models become feasible.

2.5 Progress in ICT

Both enabling and following this change of mobility culture, the developments of ICT open a vast array of options in user applications and the integration of mobility offers. The role of smart personal electronics can hardly be overstated. Smart phones allow on-demand and individualized travel planning, improved transparency and convenience leading to entirely new mobility options. Car sharing existed prior to mobile ICT but has been dramatically changed through smart phones that allow free-floating, on-demand systems. Mobility integrator apps like Moovel by Daimler are an entirely new way of organizing (urban) mobility. The app offers point-to-point trip planning using many possible mobility options ranging from public transport (PT) to car sharing and bike sharing to ride sharing. Where available, it also allows ticket purchase and integrated billing e.g. of car sharing services. Moovel functions as an integrator of the different services and data platforms, managing this complex system to offer a simple to use and convenient service to the user (Moovel, 2014). Similar applications are emerging around the world.

ICT also has vast potential for cities, as the example of Helsinki shows: Using an app-integrated comprehensive mobility platform, the city aims to "furnish riders with an array of options so cheap, flexible and well-coordinated that it becomes competitive with private car ownership not merely on cost, but on convenience and ease of use" (Greenfield, 2014). In essence, instead of using conventional policy tools to improve the mobility offer, the city wants make driving a car obsolete by offering an all-round better alternative.

These cases show how, based on modern ICT, entirely new mobility solutions are currently emerging that not only try to satisfy individual mobility needs in the most efficient way but also offer novel business models. Instead of selling a car or a tram ride, integrated mobility providers sell point-to-point mobility to the user. While car manufacturers are expecting to continue to generate a majority of their revenues through vehicle sales, this approach promises a way for the manufacturers to be part of an evolving urban mobility mix and retain or even extend brand presence in times where vehicle ownership is stagnating and receding (PWC, 2013).

Modern ICT is widely considered a key building block of sustainable transportation also from the infrastructure side. ITS as the EU calls this set of technologies comprising for example advanced traffic management systems, intelligent traffic signals, smart ticketing or vehicle-to-vehicle and vehicle-to-infrastructure communication systems, promises large benefits (European Commission, 2013). It has been claimed that each year, in the OECD countries intelligent mobility infrastructure could add an economic value of 10 billion Euros through avoided congestion, help avoid 1 million accidents and save fuel to the equivalent of 5 million metric tons CO_2 (a 3% reduction of total transport emissions). These gains could for example come from interconnection of vehicles with the road infrastructure and better traffic management systems (Bitcom & Fraunhofer ISI, 2012; OECD, 2012). Consequently, there is considerable interest in this set of technology. As stated in a European Commission staff working document, "In urban regions, where there is limited capacity to construct new infrastructure, the current need is to optimize its use, by implementing solutions based on new technological tools and connecting different networks. ITS are promising tools to address the urban mobility policy objectives" (European Commission, 2013, p.12).

The range of high-tech projects supported by the European Union also includes ATS like PRT and other autonomous vehicles like Cybercars or high-tech buses. Since in recent years the dramatic advances in sensor technology and ICT make these technically viable today, the current efforts by the public sector focus on questions relating to legal framework (for example the adjustment of the Vienna convention on road traffic[2]) and the feasibility of real-life integration into an urban environment (CityMobil2, 2014).

2.6 Vehicle automation

A parallel yet largely distinct trend to autonomous vehicles is that of incremental automation of conventional cars. Vehicle automation is typically divided into 5 levels, reaching from 0 (no automation, driver in control at all times) to 4 (full automation, vehicle can drive itself under any circumstance) – see ***Figure 1***.

Grasping the emerging technological possibilities and reacting to the mounting challenge to the car as the dominant means of transportation, the automotive industry has been recently increasing their investments into research on vehicle automation heavily. Not without reason: leading consultants project the global economic value of highly automated vehicles to anywhere between $200 billion and $1.9 trillion per year due to improved safety, time savings, productivity gains, raised fuel efficiency and reduced exhaust fumes (McKinsey, 2013; KPMG & CAR, 2012). The direct market value of vehicle connectivity technology for the automotive companies is projected to double to $110 billion by 2020, making increasing integration of electronics and ICT into the car highly lucrative for the manufacturers (Strategy&, 2013). It is expected that cars with the capacity for fully automated driving will enter the market within the next decade (KPMG & CAR, 2012; Kornhauser et al, 2014). However, some also caution that the capability of automated cars is overly hyped. One research study estimates that by 2030, while creating a $87 billion market, 92% of vehicles with automation technology will only reach "level 2" of automation, applying supporting features such as lane assist or emergency breaking; 8% could be "level 3" automated cars like those by Google, which require extensive work to drive autonomously under some circumstances. At the same time, the report expects no "level 4" autonomous cars – able to drive themselves under any circumstance – to reach the market by 2030 (Lux Research, 2014). Moreover, legal adjustments need to be made for the introduction of advanced vehicle automation and fundamental ethical conflicts arise from it (Lin, 2014).

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[2] This UN convention is of particular importance for the automation of road vehicles since one of its provisions is that the driver of a vehicle needs to be in control of the vehicle at all times. While this may not be applicable to autonomous vehicles as it is not clear whether they qualify as cars or not, this uncertainty caused risks to the advancement and commercialization of the technology, slowing it down. The convention has recently amended to accommodate automated road vehicles (Miles, 2014).

Level 0: No Automation. The driver is in complete and sole control of the primary vehicle controls – brake, steering, throttle, and motive power – at all times.

Level 1: Function-specific Automation. Involves one or more specific control functions like electronic stability control or pre-charged brakes.

Level 2: Combined Function Automation. This level involves automation of at least two primary control functions designed to work in unison (e.g., adaptive cruise control in combination with lane centering).

Level 3: Limited Self-Driving Automation. Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic but the driver is expected to be available for occasional control. The Google car is an example of limited self-driving automation.

Level 4: Full Self-Driving Automation. The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. This includes both occupied and unoccupied vehicles.

Figure 1. Definition of levels of vehicle automation

Source: Kornhauser et al., p.5 (2014).

As experiences with fully automated cars like the one by Google show, they are significantly more precise, efficient and safer than human drivers could ever be (Simonite, 2013). A PWC study forecasted that driverless vehicles could reduce global traffic accidents from 10.8 million per year to 1.1 million per year and gallons of fuel wasted by congestion from 1.9 billion to 190 million (PWC, 2014). Particularly safety electronics in cars are becoming the norm, and a car that is not able to avoid dangerous situations may be impossible (or even illegal) to sell in the not-too distant future. Therefore it is practically mandated for the automotive industry to foster the research on automation. However, it should be noted here that vehicle automation is no panacea for sustainable transport policy. "Simulation models have shown that even the capacity gains from vehicle automation would prove inadequate to address the inefficiencies of private car use in the centers of large European urban areas" (Kornhauser et al., 2014, p.5). While automation promises benefits in road safety, it cannot fully solve issues of urban congestion or GHG emissions. Clearly, other and complementary solutions are needed.

2.7 The role of car companies

Some expect the global car fleet to shrink by as much as 99% due to large efficiency gains and improved vehicle sharing concepts enabled through vehicle automation (PWC, 2013). Whether this is accurate stands to reason – but the message is clear: Not only the car as product but also surrounding business models and the industry's structure are questioned in a highly automated vehicle scenario. Whether an autonomous car can be marketed using the same emotional strategies (excitement, speed, handling, etc.) remains to be seen. In fact, while autonomous vehicles could be less appealing to be owned privately, they could lend themselves much better to fleet operated systems. By 2020, Bain&Co forecast "new business models" to contribute to 60% of all car makers' global profits (Bain&Co, 2011).

The automotive industry at large is undergoing fundamental changes in many other ways, too. Key challenges to be named are stagnating home markets, new global market dynamics, the race for efficiency gains, changes in the value added chain, electric mobility and policy pressure for safety and sustainability (PWC, 2013; f/21, 2013). However, it is not all doom and gloom for the car companies. The emergence of ICT also offers a vast array of new ways to make the individual car be more attractive and to differentiate oneself from the competition. New lightweight materials and electric mobility allow novel designs and vehicle architecture. Car sharing and app integration provide user data and new markets. As a result, the portfolio, business approach and indeed entire corporate philosophy of car companies are changing dramatically. In other words, it is not impossible that soon, instead of embodying "das Auto." (the car), Volkswagen could become "die Mobilität." (the mobility) – something entirely unthinkable only a few years ago. The cases of the MicroCity concept by Volkswagen (Volkswagen AG, & Orange Edge, 2012) and the BMW i Mobilty Services (BMW, 2014) are illustrative. While one should be cautious in proposing that car companies will abandon their highly profitable core business model, these developments nonetheless mean that novel solutions that fit the car companies' picture of the future may have a window of opportunity.

2.8 Summary: Changes in urban mobility

In summary, we are in the midst of a paradigm shift in mobility, particularly urban mobility. Existing systems and approaches are under pressure by persistent and fundamental trends such as climate change, urbanization and demographic change; other trends like technological progress the recent changes in mobility culture are more difficult to project but are already having substantial effects on how we perceive urban mobility. To face these changes, actors of all levels are engaged in finding solutions. Cities have the highest pressure to innovate, as they are focal points of human activity but also suffer the most from overburdened transport systems. Simultaneously especially some large cities have the necessary independence and legal, economic capacity to move ahead of market trends and national legislations like the examples of the Cities Climate Leadership Group (C40) and the Covenant of Mayors prove.

In these highly dynamic times, innovative mobility technologies are becoming viable and are receiving attention as potential solutions to these issues. PRT is one of them and, as opposed to many other solutions, is available now. First applications successfully demonstrated the technical viability and potential of PRT and indicate that it may fit the window of opportunity that is opening now. The next section will introduce the concept, its history and outline its main advantages and limitations.

3. PRT: Introduction and Definition

Personal Rapid Transit (PRT), sometimes also called Automated Transit Network (ATN), is an innovative form of transport that promises to address many of the challenges of urban mobility presented above. It is characterized by small, electric vehicles for maximum 6 people that run on a dedicated infrastructure, a guideway, connecting a network of stations. These stations are constructed off-track, so that non-stop service is possible. Therefore, individual vehicles are more independent of one another than those in a line-haul system, higher average speeds can be reached and total travel times are low. Vehicles run with very short headways of a few seconds, which compensates the small vehicle size to achieve useful system capacity. Multiple physical and electronic safety measures ensure very high levels of safety and reliability. Service is on-demand and can be provided at any time of the day since no drivers are necessary. The guideways may be at-grade, underground or elevated. Due to the small, light vehicles, the guideways are sized comparable to a pedestrian footbridge, which makes them smaller and potentially cheaper and more flexible to build than road vehicle infrastructure. While the PRT vehicles are driving fully automated, a central control system is deployed to manage vehicle distribution, demand and efficient route booking. For clarity, see ***Figure 2*** for a list of characteristics a system needs to have to qualify as PRT system according to the Advanced Transit Association (ATRA).

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 level ground, 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

Figure 2. Definition of PRT according to the Advanced Transit Association

Source: Advanced Transit Association (ATRA 2003, p. 11)

Due to its unique characteristics, PRT is claimed by its proponents among others to be highly energy efficient, cheaper than other transit modes, open new space at road level and ease congestion, as well as provide very convenient transit similar to that of cars. As will be presented in the subsequent sections, it is not quite so easy. While these proclaimed advantages largely hold in both in modeling and existing demonstrators, PRT also has some specific limitations and hurdles that need to be considered.

In discussions about PRT there is often a good degree of confusion as to what exactly it is. Before proceeding, it is therefore important to clearly distinguish it from similar systems:

Automated People Movers (APMs) are common place at airports globally. Like PRT they are fully automated and drive on a segregated driveway, which is often elevated. However, like conventional rail transit systems, APMs are line-haul systems serving stations sequentially along a track. Therefore they usually stop at each station; also they typically run on a fixed schedule without on-demand options. Vehicles are much larger than PRT vehicles, often for 20, 50 or more people. This makes the vehicles very heavy, in turn requiring very robust and thus large and expensive tracks (Larsen, 2012).

Cybercars, sometimes referred to as Cybernetic Transport Systems (CTS), are small, autonomously driving vehicles similar to PRT pods but using existing road space. Since only minor adjustments have to be made to existing infrastructure, implementation may be easier and cheaper. However, since they share infrastructure with other road users, speeds are lower than those of PRT and other legal and safety questions arise (CityMobil, 2011).

Group Rapid Transit (GRT), also sometimes called "cyberbus", is functionally the similar to PRT, only that the vehicles are sized to carry larger groups of people. This leads to differences in the system characteristics: As the vehicles are larger and heavier, so is the accompanying infrastructure. Due to the larger groups sharing one vehicle, non-stop service is more difficult to arrange and speeds may be lower. However, in principle it is possible to combine PRT and GRT in one system (Niches+, 2011).

There are four PRT systems currently in operation: 1) Morgantown PRT, operational since 1972, was the first so-called PRT system although it should correctly be labeled a GRT given the vehicle size. 2) London Heathrow pod by ULTra Global PRT, connecting Terminal 5 with the business car park. 3) Masdar City PRT, Abu Dhabi by 2getthere, functioning as an undercroft transportation system, which had initially been planned to be the sole transportation system of the city but has since been scaled back. 4) Suncheon PRT, South Korea by Vectus, providing shuttle services for Suncheon Garden Expo park visitors. Its stations are not off-track however, questioning whether it is a true PRT system. These four systems are built by four different providers and are based on four distinct system designs and sets of technologies. They are described in ***Section 3.4.1***, which is recommended for readers who had no exposure to PRT so far.

Many PRT systems have been modeled world-wide as for example as feeders for business, as parts of or complete transit systems and even as the sole transportation medium for entire cities (Tegnér et al., 2007) and regions (Kornhauser, 2011). Until today, no full-scale PRT network has been built, and none of the existing systems is commercial in that it collects fares. To create a better understanding of PRT, the next section will introduce the reader to its history.

3.1 History

The idea of PRT is not new; the first concept work is credited to Donn Fichter in 1953, resulting in the 1964 publication "Individualized Automated Transit and the City". Since then substantial research has been conducted on the topic: According to Wayne D. Cottrell, by the mid-2000's around 200 articles on PRT had been published (2005). The literature includes: "technology development programs, demonstration projects, alternatives analyses, preliminary system design and layout, technical and operational analyses, economic and business case modeling, environmental impact analysis, patronage analysis, technology and network management, and cost and performance comparisons." (Carnegie & Voorhees, 2007, p.22). A good description of the history of PRT until the 1990's was written by Anderson (1998). Referring to these sources, Carnegie and Voorhees detailed the development of PRT until the mid-2000's and provide a comprehensive review of PRT (2007). PRT periodically received considerable government attention and support as solutions for urban mobility were looked for. Moreover, many semi-independent academics and consultants from Europe and the USA did considerable conceptual and analytical work on PRT and forwarded its development. The first high in activities regarding PRT was 1964-1975, mainly in the USA. Since the mid-1990's interest in PRT increased again mostly both in Europe, cumulating in the launch of the first 'true' PRT systems between 2010 and 2014.

The initial boom in PRT was initiated by the 1964 U.S. Urban Mass Transportation Act, which prompted substantial public support for PRT and other advanced transport systems in the USA. Subsequently, between 1968 and 1976, extensive research on PRT was conducted by the Aerospace Corporation, a not-for-profit organization established by the U.S. Air Force. Although substantial progress was made and evaluations of PRT were favorable, the Aerospace Corporation ended its involvement with a recommendation to continue developing the concept due to its not-for-profit character (Carnegie & Voorhees, 2007).

To showcase the capability of the technology in what has been paralleled to the space race, the Morgantown PRT system was built 1970-1972 such that President Nixon could ride it in the 1972 political elections. Due to this political agenda, severe time constraints preempted thorough engineering and learning effects, leading to several inconvenient compromises in the system design. These include heavy vehicles requiring larger guideways and stations, as well as the need for adjustments for cold weather later on. As a result, the final project costs exceeded the initial estimation fourfold. The system reached its final and current extent in 1975 and has been in continuous operations since (apart from one system upgrade) (Carnegie & Voorhees, 2007). Although the system de facto successfully demonstrated the viability and reliability of PRT systems, the cost explosion and planning difficulties seriously compromised PRT development (Anderson 1998).

In the decades following the Morgantown project, several programs in other countries world-wide showed the potential of PRT and contributed to learning about its technologies; however none of these succeeded in creating commercial applications. Most suffered from high design costs, engineering faults and/or misalignment with public acceptance and passenger comfort (Anderson 1998). The most successful of these may be the German Cabinentaxi of the mid-1970's, of which the commercial application in a Hamburg project failed only due to unexpected financial restraints caused by an economic downturn in 1980. The system is still marketed in the USA, but an application is still at large (ibid.).

The most promising PRT effort until the turn of the century was the Chicago RTA/Raytheon Program of the mid-1990's. Reacting to severe mobility challenges in the Chicago area, the Chicago Regional Transportation Authority (RTA) planned to study, develop and apply PRT for the region. Of 12 competing proposals, the Taxi 2000 system was selected and the project commenced as a public private partnership between the RTA and Raytheon Corporation. In a three-year $40 million technology development program, a test track was constructed, which successfully demonstrated the technology including off-line stations, 2.5 second headway operation and vehicle network operation. A planned demonstrator at Rosemont, IL was never built and the program was cancelled in 1999 due to a variety of reasons including a change in political leadership, financial risks, political concerns and exploding costs associated with the large needed infrastructure (Carnegie & Voorhees, 2007).

Progress continued in the 2000's: From 2001 to 2004, under the 5th Framework program of the European Union the Evaluation and Demonstration of Innovative City Transport (EDICT) Program aimed to analyze and develop PRT as an urban transport solution. The ULTra PRT system by Advanced Transport Systems (ATS ltd.), a spin-off of Bristol University driven by Prof. Lowson, was used as reference PRT technology for the analysis. The program included a demonstrator in Cardiff, Wales; feasibility studies in three other European cities; an environmental, social, economic, and cultural assessment of PRT applications; and an assessment of potential benefits of PRT for Europe. The results of the evaluation were generally favorable of PRT and identified core issues that need addressing for scaling PRT (EDICT, 2004). They have subsequently been used and referred to in other major studies like Netmobil (2005), Niche+ (2011) and CityMobil (2011).

In 2004, the state of New Jersey, USA commissioned an evaluation report of PRT as a state wide transport system. The report included comprehensive state of the art evaluation of existing PRT systems, a description of the technology's history, policy tools and an evaluation for New Jersey specifically (Carnegie & Voorhees, 2007). Four prototype systems were selected for analysis: SkyWeb Express, ULTra, Vectus, and Cabinentaxi. Findings included that PRT represents a new transport paradigm, combining elements from transit and automotive and computer networking technologies, using state-of-the-art technologies. Thereby it was found to have superior performance compared to conventional transit and interesting propositions for public transport planning. However, it was deemed too risky to proceed with building PRT in New Jersey at that point (ibid.).

From 2008 to 2011, the extensive EU research project CityMobil analyzed three ATS – Cybercars, Advanced Buses and PRT – to assess them according to social, environmental, economic, legal and technological impacts. Outputs of the project include evaluation criteria for ATS, scenario development for the implementation in cities, simulation software kits, policy maker application manuals and business cases. The PRT system evaluated was the Heathrow system by ULTra. The outcomes were favorable of PRT for certain applications and proved that it can be highly cost competitive compared to other modes of transit (CityMobil, 2011).

In 2011, the city of San José commissioned an evaluation of PRT under the name of Automated Transit Network (ATN). Notwithstanding agreement that ATN had good potential to enhance the regional transit systems particularly as an airport feeder, the ultimate recommendation of Aerospace Corporation and Arup consultancy was not to proceed with building the system. The main reason was too high a political risk due to technological and regulatory uncertainties (Larsen, 2012).

These major feasibility and research studies described were accompanied by great progress in PRT technology in the last decade, cumulating in three real-life systems starting operation in the last five years. In 2010, the first ever 'true' PRT system (fulfilling all design criteria set out in ***Figure 2***) commenced service in Masdar City, Abu Dhabi. 2011 saw the full launch of the Heathrow system, and a system by Vectus went live in Suncheon, Korea early 2014 (although this one fails on point 6 of the design criteria). One more project by ULTra in Amritsar, India seems to have stalled; more on this in ***Section 3.4***. By the time of writing of this thesis, at least another 23 PRT concepts that have been drafted at some point but not realized are listed online (Wikipedia, 2014). The reasons for success or failure of PRT concepts are analyzed in detail in ***Chapter 4***, while the next section summarizes key advantages and limitations that make it interesting to discuss PRT.

3.2 Evaluation

Given the multiplicity of existing concepts and potential combinations of design elements of PRT, finding a working concept is complex. To exemplify, Anderson (1998) compounded 46 categories of trade-off areas that need to be considered in designing PRT, leading to a total of ca. ten quadrillion (10^{16}) hypothetically possible PRT systems. But even given one particular PRT concept, it is not straightforward to assess its advantages and limitations. In the subsequent section, findings from existing feasibility studies and research projects trying to do so are presented.

3.2.1 Advantages

Reliability, safety and security

Due to the segregated, often elevated guideway, PRT is a very safe mode of transport since it does not interact with other road traffic (cars, bikes, pedestrians, etc.). In the UK, the ULTra PRT system is certified for safety under Her Majesty's Rail Inspectorate (HMRI) (EDICT, 2004). During the EDICT study, some concerns were voiced regarding personal safety and security. However, as later shown in the CityMobil study, as opposed to other ATS, the Heathrow PRT system performed very well in passenger perception regarding safety and security (CityMobil, 2011b). Additionally, the minimal waiting times improves personal safety of passengers as it reduces vulnerability at stations.

Existing PRT systems show very high levels of reliability of operation. The Heathrow system claims 99% service availability since its launch compared to 94.8-98.6% for other London transport systems (CityMobil, 2011b; Kerr, Lowson, & Smith, 2014). 2getthere reports 99.8% system available for its system in Masdar City (2getthere, 2011) and Morgantown PRT has been operating with 98% reliability or higher for 30 years (Carnegie & Voorhees, 2007). The capacity to operate in adverse weather conditions depends on the system but is generally given: Heathrow PRT copes with ice and snow using a track cleaning vehicle and Morgantown PRT installed an expensive track heating system to this end.

Transport Effectiveness and Quality

Among the main advantages found in research is that PRT practically eliminates waiting time and intermediate stops and is comfortable for the passengers. This is considered to significantly raise the attractiveness of PRT as a transit system (EDICT, 2004; Carnegie & Voorhees, 2007). In passenger questionnaires conducted at the London Heathrow PRT system in 2009, customer satisfaction with the system was extremely high, surpassing results for the previous bus significantly for 12 aspects, including image, personal comfort and space, personal safety, waiting time, environmental friendliness, and overall experience (see ***Figure 3***, CityMobil, 2011b).

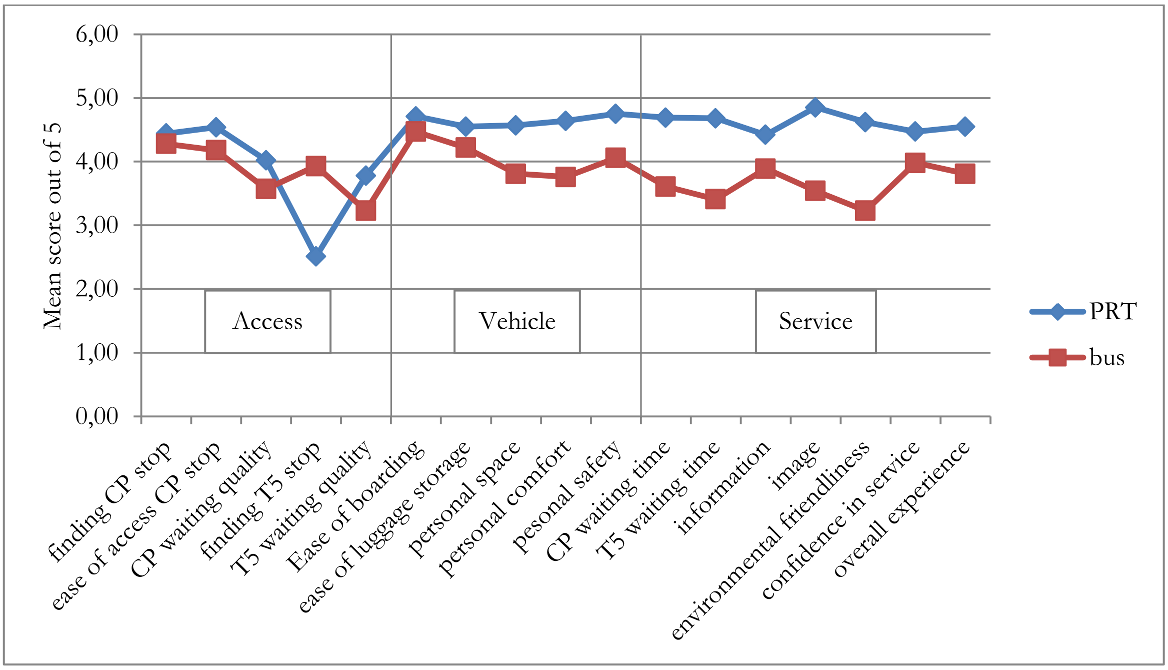

Figure 3. Heathrow Pod passenger satisfaction survey of 2009, comparing PRT and bus on 17 aspects

Source: CityMobil (2011b)

In modeling, total travel time savings are generally achieved not only compared to other public transport but also the car (Alessandrini & Stam, 2013; CityMobil, 2011; EDICT, 2004). With estimated average speeds of up to 23 mph (37 km/h), PRT systems may achieve higher average travel speeds and accordingly lower total travel times than any other urban transport system, including cars or heavy rail with an average of 20mph (32km/h) (Carnegie & Voorhees, 2007). This is possible due to the dedicated infrastructure and by locating stations off-track, therefore removing the need for stopping, which on a systemic level over-compensates relatively low individual vehicle performance (Juster & Schonfeld, 2013). By means of mathematical modelling, Lowson showed why PRT has an inherent advantage over other modes of transit – by “a factor of two or greater […] over either bus or LRT/APM (2003, p.1).

Other advantages of the dedicated infrastructure included that it virtually removes any disturbing elements from the system, thus allowing for relatively “low-tech” automation already today. Less active and passive safety features are needed in the vehicles, making them lighter. Likewise, safety certification is easier to attain (A. Smith & D. Watkins, personal communication, 2014).

In the case studies of EDICT – like in other feasibility studies, see for example Tegnér et al. (2007) and CityMobil (2011), PRT also attracted significant ridership from other modes, especially cars – which would make it useful in reducing congestion in an urban environment and further improve the environmental performance of urban transport (Alessandrini & Stam, 2013; EDICT, 2004).

Stated willingness-to-pay surveys showed that passengers would be willing to pay significantly more for PRT than for other public transport (CityMobil, 2011a; EDICT, 2004,). Whether this would hold true in reality has not been proven yet.

According to PRT engineering consultants interviewed for this thesis, PRT should in theory create the largest benefits in a larger network. Here, the ability to reach any point on a relatively dense network of stations on-demand, including hard-to reach areas that could not be entered by larger, heavier vehicles, would give PRT a unique advantage over conventional transit. Simultaneously, in such a network demand is more distributed, which suits PRT better (D. Watkins, personal communication, 2014).

Accessibility

PRT ranks well in terms of accessibility in several ways (EDICT, 2004). Firstly, it is technically able to reach points that are not accessible by means of other transportation, like narrow or steep streets where buses could not pass or environmentally sensitive areas like in the case of Suncheon PRT in Korea. Even applications running into buildings are imaginable, since the loading (weight) of PRT vehicles is lower than that of the loading requirements in footbridge design (Kerr, Lowson, & Smith, 2014).

Secondly, stations can be placed more densely than those of conventional transit modes since station spacing does not influence track speed. This could allow for shorter walking distances than for other transit modes. Thirdly, combined with low-cost operation and 24/7 service due to the absence of drivers, low-density and low-income areas could be serviced better than with regular transit (EDICT, 2004).

Finally, PRT has been evaluated well in terms of comfort, convenience and ease of use and reduced stress related to using transit, particularly for the elderly and disabled (EDICT, 2004). In the Heathrow airport PRT, this higher level of convenience was linked to the easy, at-grade entrance into the vehicles, the absence of a schedule and the smooth riding experience (CityMobil, 2011b).

Environmental performance and efficiency

Since PRT vehicles are electric and lightweight, they are theoretically the most energy efficient means of transport available. The measured energy demand of the ULTra system prototype was 0.55 Mega joule (MJ) per passenger km (pkm) (EDICT, 2004). However, in the final ULTra system now operating at Heathrow airport, the energy consumption per loaded vehicle km was measured 0.31 MJ, translating into a total energy consumption of 1.1MJ per pkm. This significant increase is related primarily to the need for empty vehicle routing and lower vehicle occupancy than anticipated (CityMobil, 2011b). While it was claimed in the CityMobil analysis that the system's energy use is about three quarters of the energy used by public bus or tram system (ibid.), other sources suggest that it is actually similar to the energy use of other transit systems, as visible in ***Figure 4***. This apparent discrepancy highlights the importance of careful system engineering, which is why considerable theoretical and engineering work has dedicated to ride sharing strategies (Muller, Cornell, & Kubesa, 2012), empty vehicle routing (Lees-Miller & Wilson, 2012), vehicle and system management (Saloner, 2012; Fatnassi, Chebbi & Siala , 2013). Nonetheless, PRT is at least as energy efficient as other modes and allows for near-zero emissions if renewable energies are used. Further energy savings would be realized in a city environment if PRT contributes to congestion relief (EDICT, 2004).

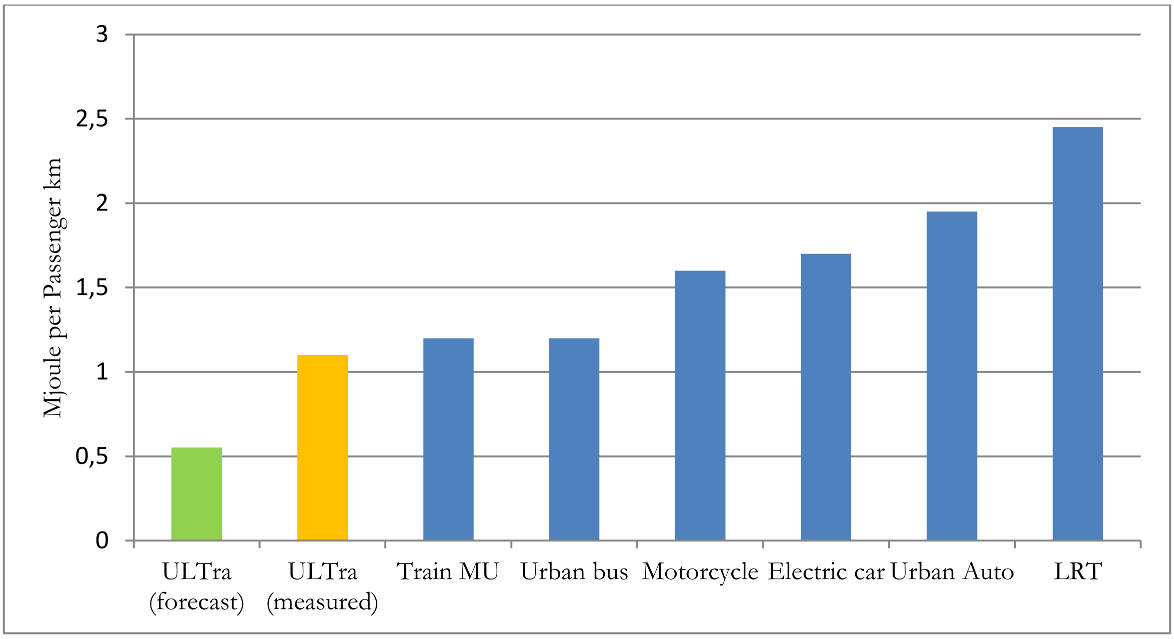

Figure 4. Energy use of PRT compared to other modes of transport

Source: EDICT (2004); 'ULTra (measured)' added by author according to data from CityMobil (2011b)

PRT is also very quiet since it is fully electric, lightweight and runs on smooth surfaces (ATRA, 2003). The ULTra system for example measures full-speed noise levels of less than 50dBA at 2.5m measuring distance (CityMobil, 2011b), quieter than an in-door conversation.

Due to the ability to elevate the guideways and build small stations depending on the local demand, the ground space requirement is very low and was evaluated positively in a recent life cycle analysis (LCA) of the Vectus PRT in Suncheon, South Korea. Here, PRT was chosen precisely because it crosses an environmental protected area with minimal intrusion (Eriksson, 2012).

Operating costs and socio-economic impacts

Social cost-benefit analyses of PRT consistently show positive net present values. Due to the low operating costs (estimated in 2004 to between 0.16€ - 0.06€/pkm; compared to ~0.18€/pkm for existing light rail transit/tram (LRT) systems; NETMOBIL, 2005) due to the absence of drivers, high energy efficiency and high reliability, PRT is expected to operate profitably and cover most of its capital costs (EDICT, 2004; CityMobil, 2011; Kornhauser, 2011). This sets it apart from conventional transit modes that usually require long-term subsidies even for operation. The light infrastructure is much cheaper to build than LRT tracks. Proponents estimate cost savings per track km to between 50% and 70% compared to LRT systems (Kerr, Lowson, & Smith, 2014; G. Tegnér, personal communication, 2014). Lifetime costs of PRT are similar to or lower those than of bus systems (Niches+, 2011). However, the costs related to PRT infrastructure create substantial controversy, as will be discussed below.

Other positive social externalities include increased accessibility, congestion reduction, air quality improvement, GHG emissions reduction and accident reduction (EDICT, 2004). Moreover, the possibility to provide convenient access to new developments on the one hand and support the densification of and traffic reduction in inner city areas on the other could make PRT a very interesting concept for example for city administrations (ibid.) and tourist agencies, real estate companies and retail (P. Nothdurft, personal communication, 2014). The social benefits spread farther than the net profits generated from the system, which can be considered an advantage of the system from a social perspective but leads to downsides and limitations from an economic point of view, as will be discussed in depth in ***Chapter 0***.

Novel transit & urban design opportunities

One key advantage of PRT certainly is that it offers new ways of thinking of and designing public transport systems. Among these, implementing PRT as a feeder to rail directly on the train platform has for example been discussed by Andreasson (2012). Building it directly into buildings could be possible as well due its low loading requirements (Kerr, Lowson & Smith, 2014). ULTra investigated the feasibility of not only running vehicles through terminal buildings at Heathrow airport but even use them to board airplanes (N. Ford, personal communication, 2014). One paper also suggested combining the PRT way with ground level bike tracks and/ or sidewalks that could then be shaded from weather by the guideway above (Schweizer, 2010). Generally, some proponents of PRT consider it well compatible with new urbanism and walkable cities (McDonald, 2011; Meggs, Rupi, & Schweizer, 2011). PRT or PRT-like concepts can also be found in more futuristic, seemingly radical urban development concepts where they may function both as people and freight carrier (Allende et al., 2008). Moreover, one could also consider a PRT system where certain stations can only be stopped at if all passengers in the pod have authorization – something particularly interesting for example for business parks or airports. An integration of PRT with highly automated city cars could also be imagined; for a discussion of this, refer to ***Chapter 5***.

Policy integration

As highlighted by EDICT and later reiterated by CityMobil, given its characteristics and expected positive social externalities, PRT could be well suited to integrate into policies relating to "accessibility, social inclusion, and regeneration in addition to sustainable mobility objectives" (EDICT, 2004, p. V; CityMobil, 2011). The feasibility of PRT as a city-wide transit system has been modeled for many pre-feasibility studies for cities around the world using various methods and assumptions (Muir, Jeffery, My, Tripodi, Shepherd & Vaa (2009).

3.2.2 Limitations

PRT have very specific caveats that are presented in the following section. Where they create hurdles to the success of PRT they will be discussed in more detail in ***Chapter 0***.

Dedicated infrastructure

As widely acknowledged in the PRT literature, building PRT guideways at-grade is not practical in most cases, particularly in urban environments, since at grade it creates absolute barriers: Different from e.g. a light rail system that can share space with cars and pedestrians, in PRT the high speeds and very short headways during peak time prohibit any pedestrian crossing. Also, allowing any non-native element to enter the guideway would reduce the system's efficiency and require much higher safety provisions. Due to these reasons, PRT must typically be elevated to avoid creation of barriers.

Visual intrusion has been found a key downside of PRT where its tracks are elevated. Even though the lightweight construction of modern PRT allows a very slender construction comparable with a foot- or bike bridge, this is a major restraint particularly in old town centers and narrow lanes (EDICT, 2004).

A related issue, the physical integration into existing city infrastructure has been named a problem. Here, not only the stations themselves have a footprint. If stations are to be kept low-cost and accessible, they are best built on ground level. Then however, long track sections of ascent and descent need to be constructed that create barriers and are likely to increase the level of visual intrusion (A. Smith, personal communication, 2014).

On the other hand, it has been shown that careful design of guideways and stations can reduce the issues of visual intrusion even in historic town centers. This indicates that people near historic city centers could accept PRT if its implementation was done with care (Hammersley, Lowson & Koren, 2010; Hitrans, 2005).

Capital costs

The high capital costs for setting up the system, particularly the dedicated infrastructure, are a disadvantage of PRT compared to bus systems (while not compared to LRT, where PRT is cheaper).

For example, the total costs – including R&D – for the Heathrow project are estimated at around £50 million; for the Masdar PRT, £20 million (Frost & Sullivan, 2012). Per-km costs for the guideways are estimated to an average of €5-6 million (NETMOBIL, 2005); the ULTra system, using relatively simple infrastructure, claims costs of ca. €3.8 million per track km (Niches+, 2011). Cost estimates for the vehicles are ranging from € 75 000 (ibid.) to £100-120 000 (Frost & Sullivan, 2012). Overall, of the total capital costs for a PRT system, 60% stem from infrastructure (guideways and stations), 20% from vehicles and 20% from control & communications set-up. They are estimated to decrease by at least 50% with scale. Operating costs for the ULTra system are ca. £1 million p.a., although fixed control center costs account for 80% - thus scaling the system is cheap (Frost & Sullivan, 2012).

There is some skepticism whether capital costs could be recovered through operations. As will be elaborated on subsequently, the large sum necessary to start a system – while low compared to other infrastructure and mobility measures – is a barrier both to market entry for new competitors and for demonstrator projects.

Capacity

While proponents of PRT claim that the passenger carrying capacity of PRT could be similar to that of a tram / LRT system, this has been a contentious point. For example, in a comparison of the Stockholm LRT system with a hypothetical PRT system, Göran Tegnér made the following calculation: The tram, at a unit capacity of 212 passengers and 5 minutes headway, has a maximum capacity of 2544 people per hour per direction (pphpd). Under the same condition, a PRT track, running pods with a capacity of 4 passengers per unit and running at 5 seconds headway would have a maximum capacity of 2880 pphpd (Tegnér & Angelov 2007). Thus in theory PRT could equal, if not surpass, the capacity of LRT and bus systems. However, system capacity can vary widely from line peak capacity, as ***Table 2*** shows.

Table 2. Maximum line versus system capacity and actual daily ridership of current PRT systems

	Max line capacity (pphpd)	System max capacity (pphpd)	Average daily passengers
Heathrow	2400 (7200 projected)	656	800
Masdar	2880 (7200 projected)	300	700-1000
Suncheon	5400 (7200 projected	1313	N/A

Source: Advanced Transit Association (ATRA, 2014)

Factors influencing PRT capacity include specific track throughput, headways, station capacity and others like network management and empty vehicle routing (Delle Site, Filippi & Usami, n.d.; Tegnér & Angelov, 2007; Dylan, 2012). The throughput capacity of stations for example depends among others on the number of berths at that station, passengers per vehicle, and the flow management and layout of the station. Different berth designs also have substantially different capacities and have impacts on vehicle management and congestion management (Dylan, 2012). As stated by one interviewee though, with appropriate design, stations may be laid out to have sufficient capacity even to disembark passengers from a jumbo jet (N. Ford, personal communication, July 2014).

Since urban PRT would function as network, direct comparisons of point-to-point capacity not only become difficult but also lose meaning since the distribution of stations and passenger destinations (=demand) substantially impacts the flows of the system. The more stations exist in a system, the more distributed the demand is likely to be. It was therefore questioned by two interviewees whether it is a good strategy of PRT proponents to engage in the discussion on peak capacity for PRT; and if so suggested to use a suitable tool like a passenger destination matrix at an early stage of the discourse to avoid misunderstandings (Watkins & Smith, Arup, personal communication, 2014). Such a matrix shows the journeys from all points in a given network to each other instead of simple point-to-point demand – which is more useful for analyzing a network transit mode like PRT.

Safety & safety perception

While the existing PRT systems have been rated high both on operations reliability and safety and perceived personal safety, concerns are sometimes voiced regarding safety for vulnerable demographic groups, like children and women travelling alone. The Absence of a driver and fellow passengers in a small capsule could potentially attract perpetrators. Whether surveillance cameras are fully effective in preventing crime in empty public at all times spaces is debatable – although also the presence of bystanders does not always provide safety. Depending on the location of an urban PRT system and the demographic segments of passengers, this would have to be considered very carefully, as even isolated cases of crime could be very damaging to the reputation of the new technology. While the existing PRT systems show no indication of such problems, this is a concern particular to ATS and must be taken seriously.

Environmental impacts

Depending on the choice of some key design criteria, the environmental performance of PRT can differ substantially as emphasized for example by Thompson & Brooks (2010). Particularly the need for a dedicated guideway raises questions about the overall environmental advantages of PRT over other modes of transport (T. Sauter-Servaes, personal communication, 2014). In the LCA by Ericsson it was found that overall, compared to other modes of transport, PRT reduced GHG emissions slightly and acidifying emissions increased a little mainly due to the construction of the steel guideway (2012). This was the main contributor to all emissions during construction and end-of-life phase of the system. The steel guideway of Vectus was found advantageous over a concrete one. During operations, the choice of electricity was found to be the paramount determinant of emissions: Choosing renewable energy sources, emissions in operations could be reduced by as much as 95%. It was also found that choosing energy supply by rail instead of battery would reduce the overall impacts of the vehicles by 50% since batteries would require frequent changing and providing for charging times of the vehicles would demand a larger amount of vehicles (Eriksson, 2012). Given these results particularly regarding the guideway, one could therefore question whether PRT is an effective or even cost effective way of reducing GHG and other emissions. It should be considered though that the Vectus system is considerably heavier than for example the ULTra one, whereby the associated infrastructure and its environmental impacts would be expected to be lower.

These are some central inherent issues and limitations of PRT that determine its capacity to fulfil its promise to be a sustainable mode of urban transportation. Weighing its advantages and limitations, several studies evaluated PRT accordingly. This will be the topic of the next section.

3.3 Suitable applications

While PRT was conceived as an urban mobility system and developed accordingly, more recent studies qualified much more where it would actually be suitable. Carnegie & Voorhees (2007) identify the following areas:

- Areas with many destinations and a mix of land uses that require significant local circulation throughout the day, additionally to peak hour demand;
- Park & Ride applications and other nodes that provide intermodal connectivity;
- Areas suffering from congestion and/or limited access
- Areas where parking is expensive

In these circumstances, they argue, it could be designed as easily scalable system to allow incremental extension of an initially smaller demonstrator system. They furthermore expect that initially PRT would be implemented in non-residential areas, where potential community impact and disruption is low (Carnegie & Voorhees, 2007).

In a market analysis from 2008, re-cast 2012, Frost & Sullivan identify 10 potential fields of application for PRT, see ***Figure 5***. Of these, Frost & Sullivan identified the airports, industrial campuses, new urban developments and eco towns (2008) and hospitals and tourist attractions (2012) as main markets and found around 700 (2008), later 1000 (2012) suitable applications globally based mainly on pre-feasibility studies conducted by ULTra.

These were done on a case-by-case basis, including a variety of criteria including "the business case and return on investment, additionally issues such as visual impact, accessibility, carbon and other local pollution savings" (N. Ford, personal communication, 2014). According to their analysis, airports would be the dominant market for PRT applications in the short to medium term. To realize the full potential of PRT and make it a significant contributor to a new global urban mobility paradigm, additional investments and partners would be needed to scale up & professionalize the systems (Frost & Sullivan, 2008; 2012).

- Airports
- Industrial campuses
- New urban city developments
- Eco Towns
- Hospitals
- Tourist attractions
- Park & Ride
- University campuses
- Countries with hot climate
- Extensions of alternative transport modes

Figure 5. Potential PRT fields of application

Source: Frost & Sullivan (2012)

Maybe the most methodologically rigorous analysis of suitable applications of PRT, the CityMobil project (2011) found that of the analyzed systems (CTS, cyberbus and PRT), PRT performed best regarding transport performance and emissions reduction. Its ideal applications would be

- small to medium sized cities (up to 200 000 inhabitants) with low to medium density,
- as public transport system in small mono-centric cities,
- as transit feeder system (including Park & Ride) for suburbs, or
- servicing major activity hubs.

Thus, while these sources differ somewhat in their focal points, it should be clear that PRT is unlikely to become an urban transport mode satisfying all transport needs as its proponents long have claimed. In centers of large cities, which are particularly plagued by negative externalities of road traffic, it may not be the best option; and if so, its role would likely be limited to a supplement to existing high capacity transit systems, thereby supporting the modal shift to those. Instead, it is likely going to be restricted in the medium term to special applications outside of dense urban areas where its application is less intrusive and more experience can be gained on its advantages and caveats; in the long run its fields of applications could move more towards supporting urban transit systems.

Most interviewees to this study supported these general findings. Several of them suggested that PRT would find its place not so much in already industrialized countries but best in countries that are growing fast and are still developing their public infrastructure: Here it would be competing less with existing opinions on transit systems and could more easily become the sole mode of public transport for some cities. European cities were deemed less suitable by the experts since they frequently have historic town centers where the visual intrusion through PRT would likely be considered too much, and where politicians tend to be more conservative and risk-averse.

3.4 PRT: Status quo

The following section will present a status quo of PRT as of August 2014. Thus answering Research Question 1, the existing PRT systems will be described, recent activities presented and a brief market evaluation performed.

3.4.1 Existing systems

Morgantown

The (in)famous Morgantown PRT on the West Virginia University campus, USA, was the first ever PRT system to be built – with considerable problems as described above, such as the high construction costs of around $125 million (plus land costs) (ATRA, 2014a). Given its large vehicle size and lack of on-demand service it is also not strictly speaking a PRT. Nonetheless it is considered the first lighthouse project and proof of concept for the technology. Since 1975, over 83 million people have used the system comprising 71 cars travelling up to 30 mph (48 km/h) on the 8.7 mile (14 km) track connecting 5 stations (WVU, 2014). The tire-based cars carrying up to 18 people each are based on a Dodge truck chassis and electrically powered through a power line embedded in the side of the track (ibid.). The system has run with extremely high reliability rates and no serious injuries and carries two million passengers per year with a peak capacity of 30 000 passengers per day (Carnegie & Voorhees, 2007), 4800 pphpd (at 15 seconds headway) (ATRA, 2014a). During school year, an average 15 000 passengers are transported per day; university staff and students ride for free and non-university members pay $.50 (WVU, 2014). This makes it a main means of transport on campus, circumventing the "highly congested" roads of the Morgantown campus (ibid.). Although the system now requires a major overhaul, a 2010 cost benefit analysis found it preferable over replacing it with a substitute bus system ($144.5 million vs. 260.2 million) (N/A, 2010).

Masdar City

In late 2010, the PRT system supplied by 2getthere started operation in Masdar City, Abu Dhabi. 10 vehicles service 2 stations 7 days a week, 18 hours per day. The journey across the 1.7 km guideway takes under 2 minutes at a maximum speed of 25 km/h (higher speeds are avoided to preserve energy). Maximum capacity is 300 pphpd, with the system servicing between 700 and 1000 passengers in the first 10 months of operation. Each pod can carry up to 6 passengers plus luggage and is wheelchair accessible (ATRA, 2014a).

The system navigates by means of a combination of technologies. Passive magnets embedded in the road surface every 2 meters provide reference points to the Magnet Measurement System. An electronic Vehicle Control System and a Guidance Control System locate the vehicle's relative position in the system, control its drive controls and navigate it along the path marked by the magnets. 2getthere claims this system to be very low cost (avoiding physical guidance through infrastructure) and robust (not depending on visual conditions) (2getthere, n.d.).

Originally PRT was planned as both personal and freight transport system for the entire city, running in an undercroft system beneath the ground level, which would be pedestrian only. However, shortly after the commencement of the system this approach was cancelled due to several reasons. For one, it was found that elevating the entire city was too costly, particularly since the Masdar project itself ran into funding issues and had to be scaled back (PRT Consulting, 2010). This problem was amplified when practical experience showed that running special delivery vehicles and emergency exit routes on the same infrastructure as PRT vehicles created difficulties with right of way. Thus violating one fundamental principle of PRT – separating it from other traffic – this impinged on its performance (ibid.). Moreover, as one interviewee reported, those vehicles appeared to pose a problem for the PRT system's magnetic nails embedded in the ground (M. Briggs, personal communication, 2014). Additionally, the PRT tracks had to follow the city road layout itself, which is windy, narrow and discontinuous to reduce wind flows. This structure did not lend itself well to the needs of the PRT system, demanding adjustments that reduced performance even more (PRT Consulting, 2010).

Heathrow

After around ten years of technical development accompanied by extensive evaluative research (EDICT, CityMobil), the £30 million ULTra PRT Heathrow pod commenced operation May 2011. 21 4-seated, wheelchair accessible vehicles are servicing 3 stations through a 3.8km of guideway connecting Business Car Park One at Terminal 5 with the terminal. The tire-based, battery powered pods run on concrete tracks on the mostly elevated steel guideways with top speeds of 40 km/h and minimum headways of 6 seconds (ATRA, 2014a). The pods keep to the track through vehicle based laser guidance and are controlled through a Central Control System. A fixed block detection system in the track provides an additional safety feature by guaranteeing separation of the pods (ATRA, 2014a). Journey times are 6 minutes (compared to around 18 minutes of the previous bus shuttle) with nearly zero waiting time (ibid.). At a maximum capacity of 656 pphpd (assuming full occupancy), the system runs upwards of 20 hours per day at a reliability of over 99.%, replacing the bus shuttle service and thus 70 000 bus journeys per year (Ultra Global, 2013). Passenger satisfaction is very high as established in a representative scientific survey of 2011 (CityMobil, 2011b).

Suncheon

Constituting the latest PRT project to reach completion, the Suncheon “Skycube” was inaugurated April 19, 2014, connecting the Suncheon Dream Bridge with Suncheon’s Literature Center (POSCO, 2014). A 4.6km, elevated, bi-directional rail guideway connects the two stations with minimal impact on the sensitive wetland (ATRA, 2014a). with 40 wheelchair accessible capsules for 6 to 9 passengers plus luggage the system can service up to 1313 passengers per hour at top speeds of ca. 50 km/h . The capsule are captive on the running rails, running on electricity provided through a contact rail (ibid.). Having been developed in Sweden it is compliant to international Rail Vehicle Accessibility Regulations (RVAR) for accessibility (ibid.) and certified by the Swedish Rail Authority for passenger transport. With only two stations, the system does not exhibit off-line stations (ibid.), which would be crucial for a network-sized application; however the technical feasibility of this was proven in the Swedish test track (Gustafsson, & Lennartsson, n.d.). It was not possible to find an evaluation of the system so far (in English). As of the writing of this thesis, the website of Vectus appears to be offline.

A detailed technical comparison of the existing PRTs is available on the ATRA website (ATRA, 2014a). For more details regarding the PRT companies behind the systems consider the Frost & Sullivan market forecast (2012). The following paragraphs summarize recent activities in the field of PRT.

3.4.2 Recent activities

Thales: update Morgantown PRT

In April 2014, a train control and fare collection system upgrade was commissioned to the Morgantown PRT. It will include “Communications-Based Train Control (CBTC) system, Automatic Fare Collection system, Passenger Information system, Platform Display Signs, New Central Control Equipment, and Steering Rail Design equipment”, to be delivered as turnkey solution complete with “integration, testing and validation, safety assurance and training for the new systems” (Thales, 2014). The reason for this upgrade was the ageing of the system causing several problems. In recent years the reliability has dropped to a “not satisfactory” 93 to 98%; also, operational costs had increased due to the shrinking market for replacement components and the original supplier ceased technical and vendor support (WVU, 2014a). Thus based on a 2012 Master Plan the system is currently being overhauled in a three-phase modernization plan that will cost a total of around $100 million (ibid.).

The upgrade is scheduled to be operational by 2016. Thereby one more actor has entered the market for PRT systems, which was considered important by one interviewee for the sake of more competition (personal communication, 2014).

2getthere: Efforts in Asia

Despite the setbacks in the Masdar PRT, 2getthere, remains active. Earlier this year the company celebrated the 1 millionth passenger in that system, claiming a patronage four times higher than initially expected and a system availability of 99.4% (2getthere, 2014). Given these performance indicators the company sees this as a proof for the technical success of the system. Celebrating 15 years of cooperation with UAE based United Technical Services with who the system was developed, 2getthere reported "pursuing projects in Qatar, Kuwait and Saudi Arabia in addition to the United Arab Emirates" (2getthere, 2014a). In June 2014, 2getthere signed a cooperation agreement with major public transport provider SMRT international Pte Ltd in Singapore to get exclusive rights to supply its automated transport system to the country and operate them in East Asia (2getthere, 2014b).

London Heathrow: possible expansion

After the successful launch of the Heathrow pod, a feasibility study had been performed to extend it to the remaining terminals (Thompson, 2012). Early 2013, ULTra and Heathrow Airport Ltd. announced to build additional – but for now not connected – pod systems between terminals 2 and 3 and their respective business car parks (Ultra Global, 2013a; Heathrow Airport Ltd., 2013). While the interviewees who had previously been engaged with ULTra in the Heathrow project also referred to these plans, they were not able to give additional details (personal communications, 2014); nor was it possible to find more recent information on the project online.

ULTra PRT: Amritsar, India

After the Heathrow pod, the next project by ULTra Global PRT was a full scale urban PRT network in Amritsar, India. With 7 stations along an 8 km guideway and more than 200 pods, this would not only have been not only the largest PRT system globally by an order of magnitude but also the first to apply the technology in an urban environment and collect passenger fares under such conditions. It was meant to transport 100 000 passengers per day between the city's train station, bus terminal and its main landmark, the Golden Temple. Thereby it was intended to save around 35% of the temple's visitors around 30 minutes of journey time. Based on a build, own, operate transfer (BOOT) scheme it was planned and financed entirely by private parties (Ultra Global, 2011). Ground was laid in December 2011 stirring international attention (Witkin, 2011). However, until today it has not moved past the planning stage; by September 2013, the project had stalled and seemed to be close to cancellation (Mohan, 2013).

Alleged reasons for this were:

- Questions about financial viability, also compared to coinciding plans for a BRT system;
- Visual intrusion of the elevated guideways passing by other landmarks in the city;
- Protests of local vendors that feared losing business of bypassing site visitors;
- Residents' concerns regarding the guideways' impacts on ventilation, sunlight and privacy issues; and "doubtful credibility" of the single one company that reacted to the tender for the project, PRT fairwood – a joint venture of ULTra PRT global (ibid.; Paul, 2014).

As Interviewees to this thesis confirmed, the tendering process was a major hurdle to the project since the lack of real competition made it prone to questions regarding competition law (personal communications, 2014). The local government also appeared to be cautious about supporting the project because of its contentious nature. During the times, important regional elections were held (Paul, 2014). As will become clearer in the analysis in ***Chapter 4***, the problems facing the project here in India also surface as general inhibitors to PRT. While there is no news – including from the interviewees – of the project being finally cancelled, it appears at least stalled indefinitely.

Systems announcing technology demonstrators:

With a first technology demonstrator announced to be built on the Israel Aerospace Industries campus in Tel Aviv until 2015, the skyTran concept is aiming to join the group of working PRT systems (Wakefield, 2014). Using an aerodynamic, two-person capsule suspended from a rail using magnetic levitation (maglev) technology, the system is claimed by its inventors to be more energy efficient, lower in maintenance and much faster (up to 240km/h) than existing systems. Thereby the company understands its system as "next step" of PRT (skyTran, 2014). It is unclear however how and whether off-track stations are part of the design, without which the system would not strictly speaking be a PRT system anymore and average speeds would decrease substantially.

MISTER (Poland), similar to the skyTran system, uses a hanging clamped rail system but without the high-tech maglev technology. It claims to be able to implement off-track stations, which other approaches found technically too difficult to implement and to be significantly more economic than previous designs (MISTER, n.d.). The company behind MISTER applied for $10Million R&D funding under an EU development program in 2010 and was looking for private investors to match these funds for building a technology demonstrator (MISTER, 2010). Since then no further news was found nor did any of the interviewed experts mention any activity. It must therefore be assumed that – at least for now – the MISTER concept is not able to supply a functioning system.

Several other concepts are in the conceptual phase without an existing technology demonstrator. According to the interviewees, interest in PRT seems to remain high as interviewees knew of project feasibility studies globally in places such as the USA, Brazil, India, Singapore, and South Korea (personal communications, 2014). However, these appear to be in very early stages as no details were known.

3.4.3 Market forecast

Based on the circa 1000 possible applications globally (see ***Section 3.3***), in 2012 Frost & Sullivan estimated the total potential market for PRT at £5.1 billion provided 170 of these at an average project size of £30 million (similar to the Heathrow project) were to be commenced by 2016. However, as the consultancy points out, this would require further efforts such as the establishment of international standards, scaling and streamlining production as well as additional investments and a rapid uptake of new projects (Frost & Sullivan, 2012). Currently, market growth is constrained by limited scalability due to lacking capacities of the small PRT development companies. Frost & Sullivan estimated that each of the 3 companies could produce a maximum of 1 system p.a. until 2016, meaning a total of 9 systems being commissioned until then at a total volume of £270 million (ibid.). With the engagement of Thales, there are now 4 companies supplying systems or system components to PRT (and PRT-like).

The PRT market is therefore clearly at a nascent stage, where little competition or market dynamics can be observed. If PRT were to become a mainstream mobility solution, the overall market potential could be much bigger. If all 1000 identified applications were realized, according to the same assumptions the market would grow to around £30 billion. These market projections are of course based on very simplistic assumptions. With more applications particularly in urban settings, systems would likely grow in size, financial volume and vehicle number. The planned Amritsar project with around 200 vehicles is instructive. Meanwhile, economies of scale would reduce costs of all system components, improving economic feasibility.

While showing a significant market, the relative scale of PRT remains miniscule compared to the automotive sector. If the average system size stayed small (around 20 vehicles per system) as assumed in the Frost & Sullivan forecast, this would mean only a total number of vehicles of 20 000 – less than the over 26 000 cars produced by the Volkswagen Group *each day* (Volkswagen Aktiengesellschaft, 2013). Even a ten-fold increase in size would be barely comparable to the scale of automotive production.

3.5 Overall potential impacts of PRT on European urban mobility

While PRT had been conceived as urban mobility solution and earlier studies up to EDICT had a very optimistic tone regarding the potential of PRT for urban mobility, CityMobil and other recent detailed studies qualified and limited these expectations substantially. According to the market forecast by Frost & Sullivan, impacts on urban mobility at large, particularly in Europe, appear small with only a handful of applications appearing suitable in the medium term (2012). All interviewed experts firmly agreed to this but also expected its impacts to be large in the place where it is built (personal communications, 2014).

As discussed in ***Section 3.2.2***, PRT does not have the capacity to function in high density areas and will therefore have only minor implications for city centers of large cities. Here it could contribute to car-free mobility policies by supporting modal shift. Its main impact could be in small to medium sized cities that so far often face the problem that demand is insufficient for an extended high quality transit system. Therefore these cities tend to be more car-dependent, and PRT could help break this trend. However, as shown by several feasibility studies it may also attract some ridership from other modes of transit, which should be taken into account by policy makers. Moreover, due to its need for dedicated infrastructure, scaling will be slow and many applications will not be possible due to locally specific restrictions. At the same time, it is precisely the infrastructure that may make it highly valuable in particularly difficult-to-reach situations, offering solutions other modes could not.

It is unlikely that PRT could replace the car for urban mobility entirely even in successful applications. For one, while it offers service superior to that of conventional transit, it remains bound to defined routes and stations, thus not entirely reaching the flexibility of a car. Here, it competes with CTS and like it could be combined with extensive pedestrian zones, thus supporting car-free areas. For another, since additional track length and stations increase the costs, space requirements and potentially complexity of the system, it seems unlikely that in practice a PRT network would be scaled and densified at will. Instead, particularly for first applications, it would be most useful to apply it sparingly where it can add the largest value. The flexibility and reach of PRT is therefore unlikely to rival that of individual cars for the foreseeable future. For another, PRT pods remain a shared space with little potential for individualization. A car allows its owner to have a 'home away from home' – a psychological fix point in public areas. In a PRT pod the passenger has to take all belongings with her at the end of the trip. Thus, in some important ways it does not equal the offer of the car; both have their distinct advantages and disadvantages. With the spread of car sharing and vehicle automation, these comparisons will change dynamically.

Due to challenging political, economic and socio-cultural conditions in the EU (as discussed extensively in ***Chapter 4***) several interviewees suggested that PRT companies should focus on other markets for the time being (personal communications, 2014). While this thesis focuses on the European context, general advantages and limitations of the technologies are equally valid in contexts of other countries, too.

In summary, PRT could play a role in supporting more sustainable urban mobility policies overall if and where it is scaled, but is not a panacea. As presented in ***Chapter 0***, until then it has to overcome some formidable challenges.

4. Challenges in Implementing PRT

Clearly, there are factors that restrain the deployment of PRT. Identifying those is the aim of RQ2 in the subsequent chapter. The expert interviews conducted for this thesis delivered valuable insights into current hurdles – and drivers – for the technology. Before turning to the analysis of the interviews, experiences from some very instructive studies will be presented.

4.1 Lessons from past experiences

The Chicago RTA/Raytheon Program was a promising PRT effort, which still ultimately failed and is instructive for future projects. Through design iterations, the final Raytheon PRT design became significantly heavier and wider than the original draft, requiring a guideway almost twice as wide and heavy as the initial design. Consequently, costs, visual intrusion and complexity increased, which reduced the economic justification, public acceptance and political support for the final system. Over the time of the project, leadership in the RTA changed, which, seeing the growing complications in the project, cancelled the program in 1999. Key lessons learned from the project were that light weight design, cost control and political leadership are vital to the success of a PRT system (Carnegie & Voorhees, 2007).

The Netmobil study, referring back to and expanding on the EDICT results, identified issues of PRT in previous projects less in technical problems but difficulties in project implementation and long-term political commitment (2005). It was pointed out that standard procurement procedures were not well suited for this novel technology, investment risks were still high and there were concerns about public acceptance due to visual intrusion through elevated guideways. Moreover, the costs for system replacement moving from conventional transit to PRT (comparing it to the replacement of copper wires with optical glass fiber cables) were considered a hurdle (ibid.).

The study further identified as difficulties a lack of reliable information for implementing parties (caused by concerns of concept proposers to release their confidential data). The multiplicity of existing yet unproven concepts caused confusion and doubts about the technical capacity and reliability of PRT systems (Netmobil, 2005). All these coagulated in the situation that no one wants to be the first to implement it, stifling progress. The general risk-adversity of public actors was found to add to this issue (ibid.). Reviewing historical PRT projects, Wayne D. Cottrell identified a similar set of hurdles and additionally emphasized the need for integrating urban design principles into PRT system planning for it to succeed in an urban environment (2006).

Assessing PRT for the state of New Jersey, Carnegie & Voorhees (2007) largely supported these findings. They also identified the need of PRT companies to firstly make use of the knowledge existing in other industries including the automotive, aerospace, defense and IT. Using established standards and components that would function well in PRT could help save development costs. Secondly they suggested developing and sharing open technology, performance and operating standards across the PRT industry. This should increase transparency and market functionality, as well as knowledge and perceived reliability of the technology for third parties. The same study also proposed a franchise-like public-private partnership (PPP) business model for building and operating PRT in order to create joint incentives for public and private actors to develop the technology.

Considering technological questions addressed to a larger extent through the then established Heathrow PRT system, the CityMobil study emphasized more the need for a full scale urban demonstrator, improved implementation guidelines for decision makers as well as further need for harmonized legislation regarding safety, security and privacy (2011). Such an implementation guideline was developed during that time by the Niches+ consortium and is available online (Niches+, 2010).

Still in its PRT market assessment of 2012, Frost & Sullivan pointed to the problem of the lack of commercial schemes and consequent detailed knowledge of the systems' capacities as well as low awareness among third parties of the system's characteristics and benefits. The resulting absence of long-term political commitment and public funding to move ahead with new projects was found to stifle progress. The ongoing lack of industry standards and suitable regulations continued to form a barrier according to this study (2012). The findings regarding technical and regulatory uncertainties were confirmed in the San Jose feasibility study, ultimately leading to recommendations against moving forward with it (Larsen, 2012).

In summary, reviewing literature on PRT from approximately the last decade reveals that on the one hand, interest in PRT has continuously increased as first real-life demonstrators started proving the concept technically and larger studies supported its proposal. Technological problems have therefore diminished, although not disappeared altogether. On the other hand, clearly the risks and uncertainties associated with PRT persist until the last reviews from 2010 to 2012. These are primarily of political and economic nature. The analysis of the current drivers and hurdles to PRT as based on the expert interviews follows now.

4.2 Current drivers & hurdles: Quantitative analysis – an overview

One goal of the interviews was to gain an understanding of the drivers and hurdles of PRT as its stands today. The limitations inherent to expert interviews in terms of validity and reliability, as laid out in ***Section 1.2***, should be kept in mind. Controlling for the different backgrounds and levels of knowledge on PRT of the experts, no relevant differences in their answers could be found apart from where it will be discussed explicitly.

Using Maxqda the interview transcripts were coded according to the PESTLE categories and the four major PRT components (pod cars, infrastructure, system management and vehicle automation).[3] This made it possible to structure not only which PESTLE categories but also what PRT system elements would be drivers or hurdles for PRT. Moreover, using a relations matrix the tool allowed some inferences which elements relate to each other by showing how often they were named together by the interviewees. The results from this quantitative analysis of the interviewees give a useful indication of which factors were named most frequently be the interviewees. They must however be read with care since the sheer count of referrals to a

[3] Two interviews were excluded from this because they were very short and were more informal than the other interviews, not following the guiding structure and rather focusing on specific examples. Key statements from these interviews are still used in the qualitative analysis of the drivers and hurdles.

factor does not necessarily signal its importance. Nonetheless this approach gives some structure to the debate, which is why the quantitative results will be presented now, upon which the more in-depth qualitative debate follows.

A glance at the distribution of accumulative answers regarding drivers for PRT (*Figure 6*) reveals that it **is its technically based capabilities that are strongly in its favor**. Of the PESTLE categories, Technological was named most often by far (135 times), followed by Socio-cultural (28), Economic (23) and Environmental (21) factors. Political (15) and legal (9) were named less often as drivers for PRT. The PRT components were not explicitly referred to often by the interviewees, receiving only 11 mentions in total. Here, the infrastructure was named most often (8).

Drivers	
Political	15
Socio-cultural	28
Economic	23
Technological	135
Legal	9
Environmental	21
PRT component	11
Total	242

Hurdles	
Political	101
Socio-cultural	39
Economic	88
Technological	101
Legal	24
Environmental	4
PRT component	63
Total	420

Figure 6. Accumulative drivers and hurdles as named by all interviewees

The three PESTLE categories that received the most mentions as hurdles were Political (101), Technological (101) and Economic (88). Socio-cultural factors received less attention (39) and legal issues were considered of even lesser importance (24). Environmental concerns were mentioned only 4 times (*Figure 6*). As will be explained subsequently, the majority of technological factors in fact relate back to political and economic issues, not representing technical hurdles *per se*. This suggests that **political and economic concerns are the greatest hurdles to PRT.** The PRT components were explicitly named 63 times as hurdles – eight times more often than as drivers. The clear and near exclusive focus among them lay on the infrastructure, which was named 58 times as a hurdle for PRT. Within this, the emphasis lay on the guideways. This hints at the **dual role the guideways play for PRT** – on the one hand **making it possible and enabling its unique capabilities,** and on the other hand being **a strong inhibitor for its success.**

The output of the Maxqda relations matrix had to be processed further substantially with excel to improve the data consistency and readability. Conditional formatting was used to help identify patterns and highlights in the data. It was possible to find some clusters both for drivers and hurdles and single out those PESTLE factors that related most to each other accumulatively. The PRT components were analyzed in the same fashion in the same table. This made it possible to see which PESTLE factors related to which component of the technology. For the relations tables please refer to *appendices C and D*.

On a general level it can be said that

1) Corresponding to the overall larger number of individual hurdles named by the interviewees, there are one and a half as many relations between hurdles (804) than drivers (499). This could indicate that hurdles outweigh drivers at this point.

2) There are relatively clear clusters visible both in the drivers and hurdles. For the drivers the relations among PESTLE factors are concentrated on **technological factors** and the comparatively **low costs** of the system; for the hurdles the emphasis lies on **political and economic factors**. This neatly corresponds both with the table

of accumulative drivers and hurdles and with the findings from previous studies – as summarized above – that found that the key advantages of PRT are resting in the technological strengths of the concept while it is inhibited mostly by political and market related issues.

3) Not surprisingly, those factors that had a high accumulative count of answers (see ***Figure 6***) exhibit the most relations to other factors in the matrix. According to the relations matrix,

    a. The most central drivers (see Appendix 0) are the unique capabilities of PRT (43), its on-demand service (34), convenience (32), comparatively low costs (32) and that it has sufficient capacity for low to medium density applications (31).

    b. The most central hurdles (see Appendices A and B) are the system's high capital costs (55), the complexity and slowness of the implementation process (46), the lack of credibility due to the absence of demonstrators (36), the high political risk associated (33), risk adversity of public actors (33) and the lack of a business case for the infrastructure (31).

   The relations were utilized to guide the qualitative analysis below and are therefore not discussed in more detail here.

4) **Both drivers and hurdles closely relate to the infrastructure**, namely the guideways that are such core component of PRT. On the one hand the infrastructure appears to be a driver of PRT by providing high quality service and a unique selling proposition. On the other hand, the infrastructure – particularly guideways – collected the largest amount of relations in hurdles of all single factors (152), particularly with those factors that are of high relevance (see previous paragraph). This shows how an important a hurdle it is for the concept.

When attempting to draw more detailed conclusions from the relations of individual factors to each other, limitations to the usefulness of this tool became obvious quickly. Since relation does not imply causation and the directionality of a potential effect cannot be read off the matrix either, the qualitative content of the interviews is of the essence to infer valid arguments.

The subsequent sections discuss the qualitative results of the expert interviews structured according to the PESTLE categories. Due to the interdependencies of the single factors it is not always possible to clearly distinguish which category they relate to, requiring the analysis to cross the categories. Nonetheless this distinction is helpful as a basic structure. The results are summarized at the end of each PESTLE segment category and jointly evaluated in the end of the analysis.

4.3 Drivers: Qualitative analysis

In the following part the current drivers of PRT are discussed qualitatively, followed by the hurdles.

Political

Being mentioned 15 times by the interviewees (see *Figure 7*), the current general political conditions can be considered in favor of PRT. Offering sustainable transportation, PRT fits the internationally ongoing and expanding *public discourse* on improving mobility. This includes particularly the European trend of reducing car use in cities and the interest in vehicle connectivity and automation (A. Alessandrini; personal communications, 2014; f/21, 2013). PRT has champions in government bodies and public authorities at different levels ranging from local to national to European (N. Ford, personal communication, 2014); the European commission for example supports research and legislative changes for the advancement of ATS including PRT (P. Mercier-Handisyght, personal communication, 2014). Also various companies from different industries watch the developments carefully and have conducted own studies into concepts similar to PRT. This includes Google who in 2012 considered PRT as commuter feeding system for its headquarters in Mountainview (Fulton, 2012). Even though these plans have since been abandoned, one interviewee reported that to his knowledge in principle Google remains interested in PRT (I. Andreasson, personal communication, 2014). Another case is the German multinational Thyssen-Krupp, a world leader among others in elevator technology who according to a source from Volkswagen has sketched a PRT-like concept itself (personal communication, 2014).

Drivers	
Political	
Supportive political climate	15
Economic	
Business case	7
Comparatively low costs	14
Available funding	2
Socio-cultural	
Appealing concept	12
Innovation acceptance	3
Accessibility	5
Fitting cultural / public discourse	7
Psychological empowerment	1
Technological	
High speeds	4
Non-stop service	1
Capacity sufficient for Low-medium density	20
Convenience	12
Better than conventional transit	1
Compatibility with automation trend	15
Addresses congestion	10
Proven reliability & safety	10
Improves existing transit	11
Low space requirements	3
"Low-tech" automation	8
Unique capabilities	21
Good in dense network & good last-mile connectivity	8
On-demand	10
Space requirement	1
Legal	
Safety certification relatively easy	9
Environmental	
Environmental performance	9
Silent	2
Electric	1
Energy efficiency	9
PRT component	
Pod cars	2
Infrastructure	8
System management	0
Vehicle automation	1

Figure 7. Drivers according to the interviewees

Moreover, like CTS, PRT benefits indirectly from the political and technological *advances made through the automotive industry*'s work in vehicle automation: For one, sensor technology has dropped dramatically in prices in the last decade – by up to 95% since 2001 –, and many previously advanced components can now be bought off-the-shelve (A. Alessandrini, personal communication, 2014). For another, the car manufacturers now push for legislative changes to allow high level vehicle automation. If they succeed and for example minimal headways of highly automated vehicles are allowed, as one interviewee mentioned this could have implications for PRT: Here, currently the 'brick-wall stop requirement' is applied, according to which a vehicle has to come to a safe stop at any moment if a potential vehicle in front of it were to stop immediately (like a wall). So far, this provision commonly applied in rail systems prevents PRT systems from applying significantly shorter headways or practice platooning. If this criterion were removed for automated vehicles it would have to be questioned for PRT as well, drastically increasing its maximum capacity and so make it more competitive (I. Andreasson, personal communication, 2014).

Moreover, *public knowledge and acceptance* of automated mobility is on the rise. Thus, while many political and technical questions remain unsolved for automated cars, PRT could benefit from this cultural and political change and be faster to implement (VW AG expert, personal communication, 2014). Last but not least, some interviewees estimated that it could fit an 'automated driving' scenario where business and ownership models change, conceptually matching with car sharing, ride sharing and the tendency of car manufacturers to embrace a role as integrated mobility providers (M. Briggs; N. Ford, personal communications, 2014). More details on such considerations will be presented in **Chapter 0**.

Thus it can be said that overall, the general political conditions for PRT are currently favorable. This is driven by the public discourse on sustainability and developments in the private sector, which will be shown below.

Economic

A core driver of economic kind for PRT is that it is relatively *low cost* (named 14 times), namely requiring *comparatively low capital investments* for a track- bound transit system and can potentially be *operated profitably*. The latter is intuitive and a clear, compelling advantage of PRT over other modes of transit that often require long-term subsidies to cover running costs. The former however seems conflicting with the strong role of capital costs as inhibitor (see the discussion on hurdles below). This can be explained by accurately distinguishing which capital costs are meant. On the one hand, PRT has an advantage in a direct cost comparison. Since the guideways can be as light as a pedestrian footbridge and the stations can be scaled small according to local demand, infrastructure costs lie 50%-70% below those of comparable LRT or trolley bus systems and can be expected to drop further with scale (Netmobil, 2005; personal communications, 2014). The cost advantage is particularly big in highly congested or inaccessible areas where an additional level of infrastructure adds the largest value and/ or elevation is inevitable. Elevating heavy road or even rail infrastructure is much more expensive and requires substantial, interruptive construction work such that the light and modular infrastructure of PRT becomes a strong selling point here (personal communications, 2014). As one interviewee pointed out, it may be possible to combine the guideways with cycle or pedestrian paths and/ or use disused infrastructure and thereby spread costs (N. Ford, personal communication, 2014). Similar ideas have been considered in the literature previously, see **Section 3.2.1**.

However, given various political, economic and technical uncertainties, it is not straightforward calculating a cost-benefit comparison for PRT. Also, costs per track-kilometer or even per system may not be as meaningful as costs per passenger kilometer. Given the uncertainties regarding carrying capacity – as discussed *en detail* in the next section –, one needs to account for a considerable risk contingency. Hence any argument of high capital costs as inhibitor of PRT is insufficient on its own but in combination with risks may become a hurdle.

And as summarized well in the CityMobil conclusion, "several case studies have illustrated the economic justification for PRT. […] CityMobil is able to provide a costing formula which can estimate the overall costs of an ULTra network to within 10%. [...] In all cases PRT shows an excellent socio-economic return, and a financial case which easily covers operating costs, and seems capable of covering capital costs at a public 6% discount rate." (2011, p. 11). Still, costs remain a core issue according not only the literature but also all interviewees of this study.

One emerging driver for PRT is novel *business models* that are oriented towards intermodal mobility. As stated previously, the car manufacturers are now starting to explore options to become integrated mobility providers where PRT could be one option to be considered. Car-sharing and emerging ICT mobility options support this trend (see **Chapter 0** for a discussion on possible interactions between PRT and the automotive industry). Without the need to wait for this to happen, several potential additional revenue sources for PRT exist today as pointed out by Prof. Lowson (2011, see **Figure 8**).

Potential revenue streams for PRT in airport applications:

- ✓ Land-use savings, combined with increased land values and accessibility
- ✓ No disruption of airport services during installation and testing
- ✓ Increased office rents
- ✓ Reduction in traffic congestion (emissions & road wear)
- ✓ Passenger travel-time savings & way finding benefits
- ✓ Increased staff productivity
- ✓ Sponsorship & advertising
- ✓ Third party partnerships (e.g. hotel user access)
- ✓ Operational savings
- ✓ Low CapEx [=capital costs] (vs. APMs) – reduced interest payments

Figure 8. Potential revenue streams for PRT at airports

Source: Lowson (2011, p.11)

Following a similar line of argument one can see the ways to monetize the advantages of PRT available for corporations and city governments – see **Figure 9** and **Figure 10.** *Potential revenue streams for PRT for business parks*.

Potential revenue streams for PRT in urban applications:

- ✓ Land-use savings
- ✓ Increased land values and accessibility
- ✓ No disruption of traffic, local services during installation and testing
- ✓ Reduction in traffic congestion (emissions & road wear)
- ✓ Improved air quality
- ✓ Reduced traffic casualties
- ✓ Modal shift away from the car
- ✓ Supporting policies for modal shift
- ✓ Sponsorship & advertising – potentially personalized
- ✓ Third party partnerships (e.g. hotel user access)
- ✓ Operational savings
- ✓ Low CapEx (vs. LRTs) – reduced interest payments
- ✓ Potential to attract national, supranational funding for innovative project

Figure 9. Potential revenue streams for PRT in urban applications

Moreover, due to automated operation, PRT could be operated economically in smaller and dispersed cities and in off-peak times where demand is not concentrated enough to warrant a conventional transit system – or if so, only with inconvenient schedules (N. Ford, A. Alessandrini, personal communications, 2014).

Potential revenue streams for PRT in business park applications:

- ✓ Land-use savings
- ✓ No disruption of business during installation and testing
- ✓ Reduction in traffic congestion (emissions & road wear)
- ✓ Increased staff productivity, travel-time savings & way finding benefits
- ✓ Automated access management
- ✓ Operational savings
- ✓ Image gains

Figure 10. Potential revenue streams for PRT for business parks

In sum, economic arguments could be favorable for PRT. It can be expected that once it matures technologically and economies of scale can be realized, it will outcompete comparable conventional transit systems economically. Making use of non-conventional revenue streams may make the difference here. Nonetheless, detailed, transparent cost analysis and risk mitigation are necessary to avoid exacerbating the inhibiting role of the capital costs.

Socio-cultural

PRT provides higher levels of convenience than other modes of transit. Overall, all interviewees were intrigued by the conceptual strengths (many of which are demonstrated in reality by the existing systems). Particularly in terms of superior passenger service through high ride quality, privacy, on-demand mobility and shorter travel times (personal communications, 2014). In fact, that it is such an *appealing concept* (12) was considered the strongest socio-cultural driver and one of its biggest overall. The notions of *psychological empowerment* and privacy attracted the attention of the interviewees of the automotive industry (VW AG experts, Scania experts, personal communication, 2014) – a finding complementary with the argument made in **Chapter 0** that PRT can in some ways be considered 'close to home' for car manufacturers. Those interviewees that had personally experienced PRT in Heathrow or Masdar were excited about the unique passenger experience these systems provide in terms of convenience, ride experience and sheer 'coolness' of the systems (personal communications, 2014).

PRT suits the *current cultural and public discourse*. Several factors contribute to this, which has not been discussed in the literature before. One interviewee pointed out the good fit of the small, on-demand pods with the ongoing trend for customized, individualized offers as well as the sharing economy (Scania expert, personal communication, 2014). It promises to offer *environmentally friendly*, safe, economical and *accessible* mobility (some of which still awaits proof, as extensively laid out in this paper and elsewhere) and appeals to the notion of sufficiency – asking "how much is needed" (ibid.). The rising *public knowledge and acceptance* of automation and willingness in some parts of the population as well as politics and industry to find new, innovative mobility solution (personal communications, 2014) all support this notion.

Moreover, one expert from Volkswagen was inspired by PRT to think of ways to customize the ride experience of PRT through modern ICT (including customized marketing opportunities inside the vehicle) (VW AG expert, personal communication, 2014). This relates back to interesting potential revenue streams also for the automotive industry. The critical discussion of ***Chapter 5*** will take up this topic in more detail.

In a nutshell, Socio-cultural factors are quite suitable for PRT. Not only is the technology capable of delivering superior service for customers which could give it an advantage over other modes of transit. Also its proposal of 'sustainable', personalized yet public mobility fits the current public discourse, attracting interest of the public, politics and business.

Technological

As found in recent years' literature and confirmed by interviewees, possibly the largest driver of PRT can be summarized in three words: *It can deliver*.[4] Describing all its technically founded advantages would be redundant with ***Section 3.2.1*** where these were outlined already. It is however valuable to learn that the vast majority of the interviewees were convinced of the core technological proposals of PRT (with some important caveats as described in ***Section 3.2.2*** and discussed in more detail below in ***Section 4.4***). This is reflected in the high count of the factor *unique capabilities* (named 21 times) as well as the clear focus of drivers on the technological factors overall. For an overview, the list of advantages as confirmed by the interviewees is available in ***Figure 11***.

- ✓ High average speeds
- ✓ Low trip times
- ✓ No or low waiting times
- ✓ Non-stop
- ✓ On-demand
- ✓ 24/7 service
- ✓ Privacy
- ✓ High ride quality
- ✓ Silent
- ✓ Electric
- ✓ Energy efficient
- ✓ High reliability
- ✓ High safety
- ✓ High performance in network
- ✓ Low operating costs
- ✓ Comparatively low cost infrastructure

Figure 11. Technologically based strengths of PRT as confirmed in interviews

Two factors are worth mentioning separately in more detail. Firstly, those interviewees with experience in PRT supported the finding from the CityMobil study that its *capacity is sufficient for low-to medium density applications* (20 times; personal communications, 2014). In this, even though a PRT system will likely not be able to run at its maximum line capacity under real life conditions, it outperforms comparable bus systems. This was underlined independently by both the project consultants and the academic researcher accompanying the Heathrow PRT project. (Arup experts; A. Alessandrini, personal communications, 2014). These also underlined its advantages in a network: under such circumstances, high point-to-point capacity becomes less important, while more customized routing is possible. For a more detailed discussion on the capacity – a focal point of academic literature – of PRT refer back to ***Section 3.2.2***.

[4] Although three more words should certainly be added: *where it fits*. See ***Section 3.3*** for details.

Secondly, the discussion of potential technical *compatibility with the automation trend* (15) and strategy pursued by the automotive industry was revealing. For one, all experts from Volkswagen and Scania were in principle open to PRT. Based on the premise that the original aim of Volkswagen was to provide mass mobility to the people and considering the current trends in the industry, the Volkswagen Group interviewees considered it in principle worth to at least inquire into the potential of PRT as a business opportunity for the corporation. Confident that the company has all necessary capacities to build and offer a PRT system, they were curious about the concept and saw a potential suitability for the car manufacturer (personal communications, 2014). Of course these opinions are of personal nature and do not represent official company policy but still may be indicative of a subtle change of attitude within the company. On the other hand however, those interviews not associated with the Volkswagen Group did not believe in an involvement of the company nor the automotive industry with PRT (personal communications, 2014).

For another, there could be options for more technically based convergence between PRT and cars. As for example the Arup interviewees mused, tire based PRT designs could one day be open to compatible highly automated city vehicles, leading to a better compatibility between the systems (Arup, personal communications, 2014). However, it should be noted that other interviewees did not deem such approaches likely. An approach like this will be discussed critically in ***Chapter 0***.

Legal

In terms of legal conditions, PRT has some advantages over other ATS and highly automated cars. Other ATS lack express permission to operate on roads – it is unclear whether the Vienna convention applies to them (A. Alessandrini, personal communication, 2014). For regular road vehicles challenges are even more formidable. A host of legal, ethical and liability questions will have to be addressed alongside technical difficulties before cars will be able and allowed to drive themselves in an urban environment (VW AG expert, personal communication, 2014). Existing PRT systems, on the other hand, are already certified under HMRI and other national safety authorities. Moreover, the industry could benefit from previous experience certifying automated metro systems and APMs, as suggested earlier also by Carnegie & Voorhees (2007).

Also, PRT can provide an exceptionally high safety case – proven through many million passenger kilometers between existing systems without any serious injury. Likewise, the existing systems have a track record of outstanding reliability (personal communications, 2014). These are valuable for each new system that so far still requires individual certification by the authorities (a potential hurdle as discussed below). This high level of safety and reliability is owed primarily to the dedicated guideways which minimize external influences to the system.

Last but not least, the developments of automated road vehicles have already started to impact the legal context globally: for example, the Vienna convention has recently been adjusted to facilitate the diffusion of automated vehicles. Even though these changes are not directly transferrable to PRT, the debate receives more attention and some factors that so far limit PRT, such as the brick-wall stop requirement, may be revised (I. Andreasson, personal communication, 2014).

Overall, there are several drivers of legal nature for PRT. These are due to its strong performance owed to its inherent technical characteristics including and especially its dedicated infrastructure.

Environmental

PRT's overall superior *environmental performance* (9 times), particularly through its *energy efficiency* (9 times) was highlighted as an important advantage of nearly all interviewees (personal communications, 2014). Several experts emphasized its strengths particularly in areas where the need for traffic improvements is the highest, i.e. where there is heavy congestion and other alternatives are either too expensive or impossible altogether (personal communications, 2014). This corresponds to findings from the literature. The idea of removing heavy traffic (freight and buses) from inner cities was considered a particularly appealing option that could be possible by using PRT for cargo (VW AG expert, personal communication, 2014). As noted by one mobility consultant, this would particularly appealing in old town centers where buses and freight traffic take a toll on air quality as well as foundations of old buildings (N. Ford, personal communication, 2014). The feasibility of such concepts is discussed in ***Chapter 5***.

At the same time, the flexibility and automation allows PRT to service especially off-peak transit much more effectively (due to on-demand service), efficiently and economically (using only as much vehicle space as needed) than existing forms of transit (N. Ford, personal communication, 2014). Thereby it could provide transit services to regions where transit is currently not feasible, supporting a shift away from car dependence to more environmentally friendly transit options. Thus PRT has arguments in its favor both under conditions of high and low demand. These arguments are not purely environmental but relate back to other factors such as political (effective political tool), social (convenience, accessibility) economic (cost-effective operation).

These advantages in its environmental performance, expansively elaborated on in the literature – as summarized in ***Section 3.2.1*** –, are a clear strength of PRT.

Conclusion: Drivers

In conclusion, not only does it seem like PRT can largely live up to its promises technically – the necessary but not sufficient condition for any innovative technology. Economic arguments speak for it too and should become stronger drivers with each new PRT system realized. These findings correspond with the quantitative analysis. Also, important political and socio-cultural conditions appear to be favorable of it and are becoming more so, benefiting from the overall discourses on sustainability and mobility. That PRT does not need clarification of fundamental legal questions (although it would benefit from it) further speaks in its favor. In order to be able to draw conclusions about whether this may be sufficient to support its diffusion, the next section is concerned with the hurdles it faces as revealed in the interviews.

4.4 Hurdles: Qualitative analysis

Political

The political hurdle most often referred to (21 times and by 10 interviewees) is the large *complexity and the consequent length of time needed for each PRT project*. This is a consistent theme throughout the PRT literature (compare *Section 4.1* above). Several reasons were identified for this. Firstly, there are always many actors involved that require significant stakeholder coordination (A. Alessandrini, personal communication, 2014). This is so partly due to the *complexity of PRT itself* especially in its design and engineering phase, as various companies are usually involved in it. Moreover, due to the *lack of design standards* and off-the-shelve systems, still each PRT system is custom-built, which requires substantially more detailed discourse with the purchaser (airports, city authority) (A. Smith, personal communication, 2014). Given the *limited understanding of PRT of third parties* and general *risk adversity of public authorities* – difficulties that permeate the body of PRT literature –, this is a cumbersome process (M. Briggs, personal communication, 2014). These issues are largely related to the PRT infrastructure, as reflected in the high count (58) this PRT component received.

Secondly, for building on public land (again an issue of infrastructure), various regulations, standards, certifications, etc. need to be considered, which creates substantial *administrative burden* (A. Alessandrini, personal communication, 2014). Particularly the need for submitting any public project to *public tender* substantially slows down and further complicates the process: There are only few suppliers of PRT systems and PRT competes particularly on criteria that conventional transit modes cannot fulfill.

As a consequence, competition for publicly tendered projects is likely to be very low, which creates a dilemma for PRT: By offering unique advantages that exclude most of the competition it risks being disqualified for the very fact of being outside of regular competition (N. Ford, personal communication, 2014). This issue has previously been identified in the Netmobil study (2005) but clearly not been remedied, as the Amritsar case highlighted. Moreover, the *dependence on public financing* is problematic inasmuch as that the financial scale of the projects is relatively large for local and city governments, while national and transnational agencies that have the required funding would not reap benefits directly. This misalignment of incentives has been identified in the literature, too.

The sheer complexity, time scale of several years and various administrative hurdles each PRT project needs to take makes it vulnerable to *political volatility*. This is particularly apparent in democratic countries with short electoral

Hurdles	
Political	
Lack of market, competition	3
Public funding requirements	8
Process Complexity & slowness	21
Risk aversity of public actors	14
Lacking demonstrators: credibility	20
Lacking understanding/expertise of 3rd parties	9
Political volatility	11
High political risk	15
Economic	
Lack of business case	19
Lacking economies of scale	7
Lack of funding	12
Limited capacity of of PRT companies	8
Capital costs	33
Economic risk	9
Socio-cultural	
Cultural change needed	13
Accessibility	1
Low innovation acceptance	9
Low public acceptance - visual intrusion	16
Technological	
Variety of PRT systems	6
Complexity	17
System complexity limited	2
Inflexible	6
Conflict with existing infrastructure & systems	20
Technologically obsolete	11
Space requirement	8
Capacity limitation	15
Lacking compatibility with existing & systems	16
Legal	
Administrative burden	6
Certification & standardization	10
Legality	8
Environmental	
Environmental footprint	4
PRT component	
Pod cars	2
Infrastructure	58
System management	3
Vehicle automation	0

Figure 12. Hurdles according to the interviewees

cycles but similarly true in other political systems. As a mobility expert and PRT consultant pointed out, an innovative system like PRT is always likely to polarize opinions, particularly in relatively innovation-adverse societies like the EU (N. Ford, personal communication, 2014). Hence there is a *high political risk* for a politician to be the champion for it. The next political cycle will likely expose him – and the project – to considerable criticism; a political successor from another party may then make it her declared goal to cancel the project. Even if it were to succeed, the political champion may not be in office anymore – which complicates the risk-benefit sharing: thus *incentives are misaligned* (I. Andreasson, personal communication, 2014). Similar arguments have been made in previous studies as outlined in ***Section 4.1***.

As a result of all these issues, there is a significant *lack of demonstrators* (second most named hurdle, 20 times by 7 interviewees) that would be necessary to finally prove the concept in an urban environment to increase its *credibility* and allow planners and investors to experience PRT first-hand (relating back to the *lack of understanding*, too): a hen-and-egg problem (G. Tegnér, personal communication, 2014). This high level of uncertainty about PRT's performance in an urban setting significantly raises the *political and economic risks* (A. Smith; Scania expert, personal communications, 2014). Those experts with experience with PRT were confident that once a successful demonstrator existed the technology would quickly become successful; some even spoke of a 'revolutionary change in mobility culture' (A. Alessandrini, 2014). While this is not a new insight either (see ***Section 4.1***), it appears that even the current PRT systems have not been able to dispel all concerns and insecurities related to the concept yet.

Economic

The primary economic – and maybe indeed overall – hurdle for PRT is its high *capital costs* (named 33 times). These costs are primarily related to the *infrastructure* needed for PRT that make up around 60% of all capital costs. The question of guideway costs was a particularly sensitive one. Elevated, but particularly underground guideways substantially increase infrastructure costs of PRT. One interviewee, researcher and expert on automated transport systems, estimated the additional costs of underground guideways at around €50 million per track-km (A. Alessandrini, personal communication, 2014). This constitutes an approximately 10-fold cost increase over the average costs of existing PRT system infrastructure of ca. €5 million per track-km (NETMOBIL, 2005). The expert also stated that according to his experience, PRT infrastructure costs would have to drop to below €4 million per track km to make it competitive. In some cases this may be the case already today as the cost estimation of Frost & Sullivan suggests, which puts system costs at £2.5-12 million (ca. €3-15million) per track km (2012).

The relatively high capital costs make investments into PRT unattractive for private investors and increases the political risks for public actors (EDICT, 2004; Carnegie & Voorhees, 2007). It should be clear that compared to other modes, these costs are in fact rather small. Still in combination with the political and performance uncertainties they form a deterrent for demonstrator projects (A. Alessandrini, personal communication, 2014) and high market entry barriers to small developers. After all, an estimated €20-30 million are necessary to develop and build first pilot systems (I. Andreasson, personal communication, 2014). It also prevents existing PRT companies from self-reliantly building demonstrators so urgently needed, as argued before. Being small engineering companies, they simply lack the funds and general capacity to do so (M. Briggs, personal communication, 2014). Illustratively, as the head of the EU funded CityMobil2 project remarked, this large financial need disqualified PRT from this project that now exclusively investigates CTS; it was not possible to find enough local administrations to shoulder the costs (A. Alessandrini, personal communication, 2014). If some partners with sufficient funding could be found, PRT could therefore be an option for the next round of EU research projects. Similarly, since PRT does not fit conventional transport mode categories (and particularly is not a type of road transport), it is difficult to receive public funding e.g. for research (I. Andreasson, personal communication, 2014). Still, as one of the interviewees pointed out, the question of infrastructure costs in PRT should not be overstated and be considered in relation to more expensive alternatives and long-term potential of PRT (A. Smith, personal communication, 2014).

The *lack of a business case* (second most important economic hurdle, named 19 times) was perceived as the key barrier for market entry for example by one interviewee from Scania. He pointed out that in talks with PRT companies he had been missing a comprehensive overview of relevant key performance indicators (KPIs) and revenue streams that could make PRT a viable business option (Scania expert, personal communication, 2014). So far, no experience exists with PRT systems applying a business model for generating additional revenues or monetizing indirect benefits (like image or productivity gains). However, as stated in ***Section 4.3***, there are numerous possible revenue streams that could be harnessed to make PRT profitable.

Unfortunately, no detailed analysis of potential business cases for PRT could be found in the literature – an omission that should be addressed. Especially ways to monetize benefits from the infrastructure would be crucial: as one expert reported, while it would be comparatively straightforward to capitalize on the vehicle operation, so far only few ideas exist to make building and operating transit infrastructure profitable (Scania expert, personal communication, 2014).

The fact that an implementation is always dependent on local structural, cultural and political conditions is problematic, creating a bundle of problems for businesses as was confirmed by several interviewees (A. Alessandrini, others, personal communications, 2014). As one VW AG expert pointed out, having few but large scale projects makes it difficult to off-set development costs, particularly if customization is necessary. Together with the *slow and complicated process* of implementation this increases the *economic risks* for a company. This not only deters companies from entering the market but also dissuades investors, reducing the *availability of funds* and thereby slowing down the process even more (VW AG expert, personal communication, 2014). This increased risk has been identified in the literature previously; however, as the feasibility study of ATN for San Jose showed back in 2012, even with a considerable risk contingency of 134% over base costs the PRT system was more economical than a comparable APM (Larsen, 2012).

In summary then, even though PRT is cheaper to build than comparable track-bound transit systems and may even recover not only operational but even capital costs, the initial capital costs form a substantial hurdle for its implementation. Rather than the costs themselves, the problem here is the mix of political conditions named above: the *risk-adversity of public actors*, the lack of competition and certification necessary for *public tenders* and the misalignment of the incentives regarding the *availability of funds* (N. Ford, personal communication, 2014). These findings corroborate those of previous studies. Many problems are related to the need for dedicated guideways and other infrastructure, which has not been clearly pinpointed in previous studies.

Socio-cultural

Hurdles of socio-cultural nature received less mentioning than others, which could make them seem less relevant than other factors. Nonetheless, they should not be discarded since any technology must be socially accepted to scale and indeed exist long term. Two important aspects stood out: the *lack of public acceptance of PRT due to visual intrusion* (16 times) and the overall need for a *cultural change* (13 times) that accommodates novel modes of transport.

Firstly, all experts were very concerned about the *visual intrusion* the guideways create. Since a large proportion of them must be elevated in order not to create barriers, this is a central point when discussing the technology. Also, as the interviewees from project consultant Arup cautioned, the physical scale of guideways and stations makes it demanding to integrate them sensitively into an urban environment – a requirement highlighted previously by Cottrell (2006). If stations are located at-grad to save costs and increase accessibility, the elevated guideway needs long sections of ascent and descent that create barriers (A. Smith, personal communication, 2014). Although it is possible to engineer this well and in a way that harmonizes with the urban landscape (Hammersley, Lowson & Koren, 2010; N. Ford, personal communication, 2014), it is an important point to consider and bring up in public engagement in order to avoid public resistance.[5] The more dense and historical the town, the more difficult to do this well – which is why several experts were pessimistic about PRT in historical European town centers (personal communications, 2014). As a general point, PRT polarizes. While proponents argue that it could be a lighthouse signaling the progressiveness of a city, others caution that it could become an expensive yet useless 'white elephant' project. These people can point to infrastructure projects that seemed to signal innovativeness at the time but became obsolete quickly. This complicated, potentially polarizing discussion could pose a political risk to a local politician, relating back to the political hurdles outlined above.

Secondly, like any innovative technology, PRT faces an incumbent system. This causes challenges that are rarely covered in existing literature. Not only economic, political and legal but also social institutions are not well suitable to its novel characteristics and require change to accommodate it. One VW AG expert, while being interested in the potential of PRT, was worried that PRT would mean too much of a 'technology jump' for users (VW AG expert, personal communication, 2014). It could suffer rejection due to the risk adversity of the majority of people which like things they know. Thus it must provide clear and substantial advantages while any disadvantage or problem related to it could quickly damage its reputation and threaten its success (ibid.). Also, the car is deeply entrenched in our cultural identity. Neither the very high costs of ownership nor the many inconveniences we experience with it (congestion, accidents, maintenance, etc.) deter many people from owning one. PRT is a challenge to this culture and will likely face often-subtle cultural resistances. These socio-cultural hurdles are often overlooked but can be of tremendous importance.

Also, current mobility trends go towards interconnectivity and improving the mobility system on the basis of existing infrastructure. PRT would go in a different direction with its need for infrastructure. It could then become an island solution with little interaction and compatibility

[5] To circumvent this problem, the head of Volkswagen Group Corporate Foresight suggested a different design. Instead of lowering the track or elevating the station platform, pods could be lowered individually to ground level for passenger access through a counter-weighed elevator-like platform. This way ascent/ descent sections in the guideway and expensive elevated stations could be avoided. Innovative solutions like these that address small yet crucial design considerations could help PRT overcome some key restraints.

with other systems, which would undermine its public support and limit its long-term success (T. Sauter-Servaes, personal communication, 2014). On the other hand, as argued above in S*ections 2.4* and *4.3*, the general public discourse of sustainability and individualization is currently in favor of PRT. Therefore the challenge for PRT is to transcend the car-based paradigm on the one hand and be compatible with the emergent one at the same time. While the costs associated with such change had been named in earlier analyses, the cultural institutional barriers associated with a paradigm shift like PRT would signify have not been focused on so far. It is a factor hard to grasp and quantify but important to keep in mind when implementing the new technology.

Summing up, although it was shown before that socio-cultural conditions are partly advantageous for PRT, there are also substantial hurdles here. The visual intrusion potentially caused by the elevated PRT infrastructure is likely to create public resistance. Moreover, changes in the mobility culture and its associated institutional structures would be necessary for PRT to succeed. Also, other trends that currently redefine mobility could in fact be rivalling the approach of PRT. It is therefore not clear whether drivers or hurdles associated with socio-cultural factors prevail.

Technological

The most paramount technological hurdles in the interviews were the potential *conflict with existing systems and infrastructure* (named 20 times) and how it may *lack compatibility with existing dominant systems* (16 times). This surfaced in three ways. Firstly, as also brought up under socio-cultural and political aspects, PRT clashes with existing mobility systems culturally and institutionally. Requiring different knowledge and understanding, attitudes and discourse due to its distinct approach to mobility means additional efforts to argue for it and 'sell' it to decision makers, investors and passengers alike, relating back to the political hurdles discussed previously. Infrastructure and institutions that other modes of transport already have in place need to be created anew for PRT; these range from legislation and certification that are required for public tenders (as discussed in more detail below) to business models (as detailed above) and physical infrastructure to run- and public knowledge how to use it. Particularly in the beginning, costly development work is required and economies of scale are absent, raising costs (personal communications, 2014). To create these institutions anew also requires overcoming resistance – as signified by the term 'path-dependency' and a substantial hurdle to any new technology, especially if expensive infrastructure is needed (G. Schrödel, personal communication, 2014).

Secondly, the *systemic compatibility* is challenging but crucial, as emphasized by several experts. If creating only rare island solutions in some particular areas, PRT could never become a widespread mobility solution. Inter-operability with other mobility solutions – be it through seamless payment options, smooth intermodal changes for passengers or also shared standards for key components or even better shared use with other suitable vehicles was highlighted as important not only for making PRT an attractive mobility offer but also economically feasible (personal communications, 2014).

Thirdly and importantly, the experts were worried about the physical *conflict of PRT infrastructure with the urban environment*. As mentioned before, sensitively integrating the guideways and stations into a dense, even historical quarter is challenging. At-grade guideways would rarely be an option here due to the creation of barriers; underground guideways would most often be prohibitively costly and elevated ones are not likely to gain public acceptance. Stations and ascent/descent sections require space that needs to be made available somehow. Moreover, how to deal with other elevated infrastructure (bridges, overpasses), treetops or raised cables are local issues that can be formidable. These problems also relate to the question of *space requirements* of PRT. All such questions are in principle solvable but further add to the *complexity* of the planning process and system, thereby increasing *economic and political risks* and *slowing* the diffusion process (personal communication, 2014).

While the fundamental functionality of PRT has been researched and modeled extensively and partially proven in the existing demonstrators, many open questions remain. This is reflected in the high amount of references to *complexity* (named 17 times) as hurdle to PRT implementation. Overall, once PRT systems are set-up they have been found to be functioning very well, creating very high quality service. The challenge lies in designing the system and setting them up (P. Mercier-Handisyght; A. Alessandrini; others; personal communications, 2014) – a difficult process not primarily from an engineering perspective but in terms of organization and stakeholder engagement. This issue is aggravated in an urban environment and is expressed in the long time scale, political and economic risks and the administrative burden (personal communications, 2014). Many of these relate closely to the need of dedicated infrastructure.

Most technical challenges are specific to the respective PRT designs. They include the limited range of the ULTra pods that require them to charge periodically – therefore needing a larger vehicle fleet and suitable station layouts –, the relatively high weight and current in-line station requirement of the Vectus system (I. Andreasson, personal communication, 2014) or the apparent sensitivity to disturbance of the 2getthere magnetic nail guidance system (M. Briggs, personal communication, 2014). The different PRT designs clearly have different advantages and disadvantages that need to be weighed in each application. Nonetheless, according to both experienced interviewees and the literature, existing difficulties should be solvable through further engineering work. That these issues are so specific to each system reflects the *variety of PRT systems* both potentially and in existence. This *lack of standardization* not only complicates the discourse about pros and cons of PRT but also denies *economies of scale* and complicates certification and legal matters (see subsequent part on legal conditions) (M. Briggs, personal communication, 2014).

Limited capacity (named 15 times) is an aspect restricting the applicability and economic feasibility of PRT, which has been covered extensively in the literature as summarized in ***Sections 3.2.2*** and ***4.2***. Still, given its current potential capacity many applications remain suitable for PRT (like feeder to other transit in small to medium sized cities or in special applications) yet have not been realized. As suggested by some interviewees, it may not be the limits to capacity *per se* but much rather in the way the discourse on transit functions. According to the knowledge of the author, such a perspective has not been taken in any analysis yet. As one VW AG expert hypothesized, local politicians are thinking of public transport particularly to solve peak traffic load situations, like commuting hours. Reliable numbers of how many people can be transported from A to B at peak capacity are therefore paramount in the discourse of transit planning. Other relevant factors such as life time costs, energy efficiency, quality of service, potential for off-peak service or comfort easily step in the background. In all these latter ones, PRT has shown to be superior to tram or bus systems – yet they are of secondary importance if a city faces severe congestion that causes palpable negative social externalities and thus justifies large investments (VW AG expert, personal communication, 2014). This hypothesis both corresponds with experiences of the author during the research process (where in several occasions when discussing PRT with mobility planners, their curiosity for the system was muted quickly when no clear number on the system's capacity could be given) and aligns with comments made by one city planner interviewed for this thesis (personal communication, 2014).

This becomes a problem for PRT as the *political and public discourses* are not suitable for its *unique propositions* and therefore disadvantage it compared to more established systems (A. Smith & D. Watkins, personal communication, 2014). It also relates back to the factor of *complexity*: fundamentally the advantages of PRT lie in the network, not point-to-point transportation. Rather than asking for one peak capacity number for the latter, thinking of passenger destination matrixes is more suitable where many demands between all points of an interconnected network are considered. This way of approaching transportation planning is more complex but could be more efficient, particularly in more extended networks where punctual demand tends to be lower since it is more spread across all nodes (D. Watkins, personal communication, 2014). Unfortunately, the existing PRT demonstrators are too small to prove the technology's theoretical advantages under such conditions. Generally, the current systems are not even close to the theoretically attainable throughput potential, which creates significant weariness in the industry and among experts whether such capacities would be attainable in real life (A. Smith, personal communication, 2014). This in turn relates back to the *lack of demonstrators* and *political risk* discussed previously.

One concern voiced by most interviewees was that PRT, while available now and compatible with the current developments in ICT and vehicle automation (as described in the respective section on drivers of PRT), might become *obsolete* before it can be scaled significantly. Since highly automated vehicles are expected within the next decade, the 'low-tech' automation of PRT and especially its infrastructure might quickly seem obsolete (personal communications, 2014). Notwithstanding doubts about the feasibility of high level automation on urban roads and its actual benefits, this outlook alone raises the perceived risk regarding the recuperation of the significant investments needed for PRT (VW AG expert, personal communication, 2014). This in turn creates doubts in politicians and investors whether it is sensible to get involved, amplifying the related *political* and *economic risks*. 'Softening' the need for dedicated infrastructure to allow for better compatibility with other automated mobility systems was suggested as remediation for this issue (Scania expert; others, personal communications, 2014), as is discussed in more detail below.

In summary, there are several, partly fundamental, technical and technological questions regarding PRT. Apart from the important question of carrying capacity, these relate mostly to the relationship of PRT with its environment. Particularly in an urban setting, socio-cultural, systemic and physical conflicts with existing systems are possible. Those interviewees with expert knowledge about and experience with PRT were generally confident that these are solvable depending on the specific system design and context. This does not mean these issues can be discarded as irrelevant: by impacting other political, economic and socio-cultural factors, especially raising (perceived) risks, they can create substantial hurdles for the success of PRT. Consequently, a successful demonstrator, carefully designed to address key technical difficulties and its development process well documented, could prove decisive in bringing PRT closer to commercialization.

Legal

One key hurdle of legal nature is the general lack of *certification and standardization* (named 10 times), which creates a whole host of difficulties. Firstly, falling outside of conventional classifications and certifications in most countries creates additional *administrative burden* for any new project (A. Alessandrini, personal communication, 2014) and complicates applications to public funding as well as increasing risks for private investors (M. Briggs, personal communication, 2014). Secondly, given the *variety* of technically very distinct PRT systems, the lack of standardization creates complexity in the planning and design phase and thus reduces *economies of scale*, adding *costs* and increasing the need for *PRT company capacity* (M. Briggs, personal communication, 2014). Thirdly, the difficulty of system specification and industry standards complicates *public tendering* processes that are required in any project involving public land and/or public funding. Here, PRT is in a dilemma: a tender must be carefully written not to exclude the competition, which would make it vulnerable to legal action by another transit provider. Since the existing PRT systems have distinct properties both from conventional transit and each other, this is very difficult to do – like the case of ULTra in Amritsar shows (see ***Section 3.4.2***; N. Ford, personal communication, 2014). These aspects are not impossible to resolve but until so form a formidable barrier to scaling PRT. Again, successful and well executed demonstrator projects could advance this issue considerably.

Other legal aspects are more specific. For one, the aforementioned brick-wall stop requirement currently restricts the legally attainable capacity of PRT, even though it is barely necessary for a computer controlled, physically segregated system like PRT (I. Andreasson, personal communication, 2014). For another, one expert noted that the elevated guideways could create *legal problems* in town centers, particularly historic ones, which are often put under monument protection laws. Here *visual intrusion* through elevated guideways could be considered detrimental to the historic monumental value of these areas, being an immediate disqualifying factor for PRT in such cases (A. Alessandrini, personal communication, 2014).

Overall, the legal hurdles for PRT are far from insurmountable and, as described in the section on legal drivers, are in fact smaller than those of other automated vehicles that share infrastructure with other road users. Nonetheless, improving the legal conditions would help streamline the project development process substantially though and reduce projects' risk of failure.

Environmental

It is clear that especially the environmental performance of PRT was not considered a problem for PRT but quite the opposite a strong advantage. Of the Interviewees, only one voiced concerns about the environmental impacts of the dedicated infrastructure in a life-cycle perspective (T. Sauter-Servaes, personal communication, 2014). As we saw in the LCA of the Vectus concept shown in ***Section 3.2.2***, this concern is valid. Still that LCA found the PRT system analyzed advantageous compared to other modes of transport (Eriksson, 2012). For widespread deployment of PRT as "green" mode of transport, the environmental impacts of the guideways and vehicles (think batteries) would clearly have to be investigated in more detail. More LCAs for the other existing PRT systems would be instructive, making it possible to evaluate PRT more accurately in multi-criteria policy analyses for sustainable transportation policy. Independent of the outcome of such analyses it can be expected that where infrastructure needs to be newly developed, the light PRT infrastructure will outperform the much heavier alternatives. Likewise, the light, electric vehicles have the potential to always have a smaller environmental footprint than any car (save maybe the smallest city vehicles).

Conclusion: Hurdles

Concluding the analysis of the hurdles, it is clear that PRT faces a wide range of hurdles of political and economic nature. Various remaining technical, and to a lesser extent also legal, uncertainties strongly contribute to these. The implementation of PRT projects remains complex and risky – maybe prohibitively so, as the low level of recent activities might indicate. This is especially the case in urban settings, where many hurdles are exacerbated by the added complexity created by the political and public nature of the projects. The PRT infrastructure, chiefly its guideways, is the cause of a majority of these issues.

Therefore a champion willing and able to push through the initial costs and risks (be they real or merely perceived) seems necessary to break through the vicious cycle of costs, risks and unproven technology. In this the author and most experts agree with the findings from several previous studies like EDICT or CityMobil.

The following section summarizes and synthesizes the results from the analysis. Also making use of the findings of ***Chapter 3***, the current state of PRT and its likely opportunities for the coming years will be discussed.

4.5 Synthesis: PRT – a solution for sustainable urban mobility?

After depicting the current state of PRT (RQ1) and analyzing its drivers and hurdles (RQ2), it is now clear that PRT as a concept is in a tragic situation. Its **unique selling points** created by its technological concept are stronger than ever. They fit the current **public discourse** on sustainable urban mobility and make PRT appear quite **economically attractive**. For the first time, **successful demonstrators exist** that support many of its technological claims as well as its ability for high value mobility service. The high **convenience** for passengers should gain it high levels of public acceptance. With its unique characteristics, it could help **address several challenges to urban mobility**, including climate change, congestion, noise and air pollution, lack of accessibility and others. Thus PRT is a good **fit with various public policies**. Not only does it achieve positive cost benefit ratios in many applications, making it politically attractive; also, the potential for profitable operation and recuperation of (most if not all) capital costs sets it apart from other modes of transit. **Legal barriers are significantly smaller** than those for other ATS. In effect, the experiences of the existing systems over the last years have corroborated the case of PRT in many ways, which increases the credibility of claims made by PRT components for decades.

Simultaneously though, there are significant hurdles that prevent the scaling of PRT in the medium term and thereby limit its overall potential (not however its benefits locally) to address the most pressing challenges to urban mobility. These hurdles include high **capital costs** for smaller actors, the lack of applied **business models** to attract private investors as well as worries about **visual intrusion**. Planning and execution is **complex** and full of uncertainties, to which difficulties associated with **public funding** and **tendering requirements** contribute strongly. These issues raise **economic and political risks** of PRT projects – to an inacceptable level, it seems, for risk- adverse public decision makers. What is more, the rapid technological development taking place globally is enabling technological solutions and business models that appear to have the potential to surpass and out-scale PRT. Therefore there is some **concern that it could become obsolete** before its true potential can be realized.

The hurdles identified in this study had largely been found in previous studies. On the one hand this is positive as it corroborates the findings; on the other hand, unfortunately it seems that since the publication of the last larger reports, the situation of PRT has changed only marginally. While the outstanding performance of the existing PRT systems have contributed to removing some uncertainties regarding performance, safety, reliability and certification, the industry is still in a nascent state and considerable uncertainties remain that prevent it from being a regular transit mode.

These hurdles are not, however, insurmountable and progress can be made. The complexities and risks associated with planning and executing PRT are manageable by expert companies if the political will exists. Multiple **revenue streams** extending beyond fare collection exist, making it possible to create a compelling **business case** for PRT in many applications. What seems to be urgently needed now is continued support of the concept by means of a next, larger and more sophisticated **demonstrator** project. This should be designed to **prove the capacity** of PRT in a network and forward **standardization** of components and procedures. Thereby political and economic risks would be reduced substantially, moving PRT closer to maturation and commercialization. Short of a real-life demonstrator it has been shown in a feasibility study in Uppsala that a visual design and planning tool can dramatically improve the chances for success by functioning as a catalyst for stakeholder discourse and allowing all involved parties to visualize the potential outcomes – thereby reducing perceived risks (Lopes & Lindström, 2012). As some interviewees suggested it may be a good strategy for PRT companies to pursue projects outside the EU and USA where funds are currently more available, political decision making is less complex and some key actors may be willing to fund PRT just to prove their innovativeness (personal communications, 2014).

At this point it seems that a **champion** with sufficient political and financial endowment to realize such a system could help PRT overcome the core hurdles identified, reaching the next level. How it could be interesting for a car manufacturer like Volkswagen to become this champion will be outlined in the next chapter.

Before moving on, some words are needed regarding **PRT infrastructure**. Throughout the research it became more and more clear that it is the blessing and the curse of the concept. On the one hand, it is a key component, enabling it to function as well as it does. Considering CTS, it is also clear that not using infrastructure is not a panacea either. Nonetheless, not without reason the infrastructure received by far the most mentions (58) and attracted the most interactions (152) as a hurdle to PRT. In the infrastructure, most of the challenges of PRT coalesce. It creates most of the system's costs, environmental footprint, design and planning complexities and is the only element that attracts negative public feedback due to visual intrusion. It also makes PRT a rather static system and binds funds in the long run. This appears anachronistic in a time where the public discourse revolves around cloud- and ICT based, flexible, digital solutions.

Moreover, while ICT based concepts are very fast to scale (think Google), the infrastructure slows down scaling of PRT considerably. This puts the technology at a disadvantage not only in terms of discourse but also structurally, as proponents of such digital solutions, like the incumbent automotive industry, have tremendous market power, making it an uphill battle for concepts like PRT. This is not to say that there are no reasons for the success of PRT: there are serious reasons for skepticism regarding the potential of e.g. car sharing and vehicle automation to address all challenges of urban mobility. Nonetheless, it is important to keep in mind how the political discourse and cultural disposition are influenced and in turn create the structural conditions for the adoption (or lack thereof) of novel technologies. Various innovation theories such as Social Construction of Technology (SCOT) (Bijker, 2009) are testimony to this.

To alleviate these problems attached to the infrastructure, many PRT experts agreed that the concept should evolve to be able to leave its infrastructure that should then only be applied where it is necessary and adding value (personal communications, 2014). Thereby becoming more similar to CTS, this way PRT could be more flexible, cost-effective and socially accepted. According to an interview with an ULTra representative in 2012, this idea of providing the infrastructure separately from the pods as a platform for other mobility systems and operators to run on has also been considered by this company (Fully Charged, 2012). Such and other options are discussed in the following chapter in the context of potential interactions with the automotive industry.

5. Critical Discussion: Potential Interactions Between PRT and the Automotive Industry

As outlined in ***Chapter 2***, there is a need for new, sustainable urban mobility solutions while a fundamental change is taking place in the automotive industry. A window of opportunity for novel solutions for individual mobility is emerging that PRT could fill. Thus, in the following pages potential interactions between PRT and the automotive industry, particularly in the context of vehicle automation, will be presented. Afterwards some issues regarding technical compatibility and in terms of business model will be discussed.

5.2 Implications & opportunities of PRT for the automotive industry

Given the restraints PRT faces, in its current form it is unlikely to seriously impact the urban car market, or mobility market overall in the medium term. For the time being it is a niche application. Still, as found in previous research and confirmed by the interviewees, where applied it could be very effective in improving the interconnection of modes, support congestion relief and be an overall "sustainable" transport solution. In this, there could be an opportunity for the automotive industry: If the car continues to lose appeal in urban areas, car companies may face a shrinking market not only here. Since cities are cradles of culture and trends, a decrease in the image of cars here could spread to society as a whole. Thereby brand value and thus achievable profit margins could decrease as cars would become less of an aspirational commodity. Moreover, particularly e.g. in China, regulations tend to 'trickle down' from the metropolises to smaller cities (from Chinese tier 1 to tier 2, later tier 3 cities) such that long term substantial market impacts can be expected from such changes. As stated before, the car companies' efforts in automation and servicizing are not least meant to counter these.

Therefore PRT could be an interesting opportunity for car companies to retain their position in urban mobility and become part of a solution to urban mobility challenges. So far, PRT has received little consideration by the automotive industry; none of the interviewees knew of efforts by the car makers to engage with PRT (personal communications, 2014). This may be because PRT is generally not well known, or because it may be considered a rival system by decision makers of car companies. This need not be so. Some potential applications whereby both PRT and the car industry could benefit include:

- PRT as alternative and complementary product
- PRT serving Park & Ride (P&R) services conveniently, connecting car parks to major nodes and facilitating the switch between transit and cars where it is too expensive / too difficult to provide parking space in the immediate center
- Integrating PRT in a mobility hub such as a MicroCity (description see ***Figure 13***)
- Integration of PRT services into mobility apps as extended mobility offer
- Using PRT infrastructure for compatible, small city vehicles as a valuable fast track through central, heavily congested or sensitive areas
- PRT as means to phase in vehicle automation
- Freight Rapid Transit (FRT) as novel urban logistics model as for example considered by Lohmann & Guala (2009)

Whether solutions like these can be realized will depend not only on their technical but also economic feasibility but also conditions of politics and corporate culture. Some aspects will be critically discussed in the following pages.

5.3 Improving PRT's business case in compatibility with automotive interests

Of the different PRT proposals, different designs have different advantages and disadvantages. However, it became clear in the foregone analysis that one key issue of PRT in city applications would be the integration into existing infrastructure and mobility systems. Tire-based designs using relatively simple guideways could have higher chances for success than rail-bound ones due to their higher compatibility with existing systems and lower infrastructure costs. For one, a system that looks and operates totally different than existing ones may suffer from low customer acceptance, since the mass market does not tend to be open to innovations and unknown technologies. Also, novel systems are always risky and rather expensive to implement particularly where other systems already exist. Integrating PRT as smoothly as possible into existing mobility structures and making it intuitive to use is thus of paramount importance. A good argument to this end has been made in the conclusion of the Netmobil study (2005).

For another, if the guideways can also be used by non-PRT vehicles, firstly the business case improves (e.g. through toll fee collection), making private investments into the infrastructure more likely. This would simultaneously reduce dependency on public funding, which could vastly improve the likeliness and speed of diffusion of PRT. Secondly, incentives would be aligned with those of the automotive industry or as it would enable it to benefit from the new system. For this to work, such vehicles would of course have to be compatible with the PRT infrastructure in terms of size, weight, and automation system, yielding control to the PRT vehicle management upon entering the dedicated guideway.

Such an approach is sometimes called a **Dual Use PRT system** where small, electric city vehicles can use the guideways. Such an approach was envisioned for example by the inventor of the ULTra PRT system, Prof. Martin Lowson (Fully Charged, 2012), and was tested in the CityMobil project (A. Alessandrini, personal communication, 2013). A technical evaluation was performed for the Texas Department of Transportation in 2007/08, albeit under rather different assumptions (Ehlig-Economides & Longbottom, 2008). Not only could opening its infrastructure to other vehicles help PRT to enter a mass market. It would also offer an opportunity for the automotive industry to partake in addressing urban mobility challenges even in difficult urban markets where cars are not wished for anymore.

For the PRT industry, such Dual Use systems would potentially 1) enlist the automotive industry to their cause, thereby gaining structurally and financially strong backers to the concept. Not only would this improve the funding situation but also increase the credibility of the concept. As concluded earlier on, the technology now needs a champion to support the implementation of larger scale projects to prove the potential of the concept in a full-scale demonstrator. The automotive industry could provide such champion(s). Political and economic risks would then reduce dramatically, removing key hurdles to PRT success. It would moreover 2) improve the business case of the infrastructure by increasing the capacity utilization and opening a significant source for revenue. Thereby, the question of capital cost / funding requirements would diminish in importance. Also, 3) PRT would benefit from institutional and technological learning through increased number and size of projects. Lastly, it might 4) improve the (perceived) compatibility of PRT with the current car-based mobility paradigm. Many innovations failed due to the difficulty of transition from an existing technology to a supposedly superior new one. Enabling cars to use PRT infrastructure and thereby creating advantages for both the existing and the new mobility options would facilitate such a transition.

Conversely, the automotive industry could benefit in numerous ways from a Dual Use concept. 1) Using segregated guideways could be a way of phasing in autonomous or highly automated city vehicles. Not only is it technically less demanding than driving in an urban environment. Experience also shows that while passengers often rated ATS like CTS negatively in terms of perceived safety and were uneasy about the absence of control or a driver, PRT did not suffer from this. Therefore, it can be hypothesized that the dedicated infrastructure could help people get used to highly automated driving in an urban context. Also, while legal concerns of highly automated driving are substantial (questions of insurability, liability, safety requirements, ethical questions, etc.), these are much less relevant for PRT as argued previously. Not only could the automotive industry therefore benefit from the good reputation of PRT in terms of safety but also introduce automation elements before aforementioned legal issues are finally clarified. This step wise approach could benefit vehicle automation tremendously, since like PRT this set of technology requires a system change for wide-spread implementation and may suffer from similar structural resistances.

2) Secondly, compatibility with the semi-public transit mode PRT could provide car manufacturers a way of retaining access to cities that otherwise want to remove cars from their roads. By means of developing a more advanced and convenient P&R for users of regular cars on the one hand and by enabling the use of PRT infrastructure for small automated city cars on the other, a car manufacturer could secure its foothold in sustainable urban mobility while offering physical locations for greater brand presence – like conceptualized in the VW MicroCity. Such measures would counter shrinking markets or even open new ones for the car as a then more sustainable mode of transport than it is now.

3) Creating compatibility of city vehicles with PRT-like infrastructure could furthermore support opening a market to the car companies that they previously could not serve: public transport. Hybrid ownership and business models would be conceivable where for example privately owned cars can function as ad-hoc PRT pods or people can own their own semi-private pods that generate revenue for them when not in use. This would create new sources of revenue both for car manufacturers and private individuals, thus reducing urban mobility costs and bolstering business against receding individual mobility in urban areas; likewise it would blur the distinction between public and private mobility that is currently not favorable for the automotive industry in the sustainability discourse. This could offer an opportunity to re-focus the public discourse from shared & public (=good) vs. private (=bad) to efficient vs. inefficient.

This relates closely to the next point 4), wherein through engagement in a sustainable transport mode like PRT a car manufacturer could benefit from brand image gains as it shows its serious commitment to becoming part of a solution to sustainable urban transport, as well as being innovative and progressive. Since branding is arguably one of the most crucial levers for sustained high profit margins, this intangible asset cannot be underestimated.

5) Finally, PRT would be perfectly suited to be integrated into a MicroCity like conceptualized by the Volkswagen Future Research department (see ***Figure 13***). A PRT system could be

integrated into a MicroCity conceptually, physically and financially: PRT could provide the advanced on-demand personalized mobility service called for by the concept, reaching directly into the building and perhaps even onto existing train tracks (like previously envisioned for example by Prof. Andreasson (2012). Thereby it would contribute to fusing public and private transportation. If PRT evolved to be partially independent of its infrastructure, this added flexibility could further enhance the usefulness of the pods within a MicroCity since dedicated station infrastructure could be unnecessary.

Developed for dense, dynamically developing cities – European and beyond -, the MicroCity is a concept of a mobility hub that integrates mobility in its various forms and other valuable services. Thereby it is intended to be a livable space that enriches life in the city. It is a system innovation that is adapted to each specific local condition in order to provide the services needed by the people locally. To do so, it is based on modular architecture and integrates different means of transport in a way each is used best, ranging from car- and bike sharing to public transit to private cars. The MicroCity uses local renewable energy forms in an efficient manner, providing the infrastructure for electric mobility and ideally also contributing to a local smartgrid. The building is designed to optimize passenger flows while offering attractive services like office spaces, shopping, and apartments. Parking is provided, ideally complemented through high value car related services such as maintenance, valet parking and trunk parcel delivery. The various services are bundled in central software such as an app or a mobility card. By combining all these factors the MicroCity improves urban mobility in a targeted manner, repositions the car in the urban context, improves urban life for people and is attractive to private investors.

Figure 13. The MicroCity Concept by Volkswagen Group Department of Corporate Foresight

Source: Volkswagen Group & Orange Edge, 2012

Since a MicroCity is optimized for flow both physically and in terms of services, both PRT infrastructure (stations, guideways) and services (payment, access systems, vehicle management) could be seamlessly integrated into the MicroCity. Also, since the MicroCity is an infrastructure measure and thus constitutes a substantial infrastructure investment that is nonetheless intended to be profitable for private investors, there should be an opportunity to create synergies between PRT and the mobility concept. Lastly – and indeed crucially – the modular, light infrastructure of PRT is perfectly suitable to the MicroCity concept, which is equally is based on modular, light-weight, even temporary architecture. Thus MicroCity and PRT could be jointly designed in such a fashion that they can be flexibly deployed and adapted according to changing local mobility needs.

These points show that there could be considerable benefits for both PRT and automotive manufacturers, specifically Volkswagen with its MicroCity concept, in fostering convergence and cooperation between the two systems. If realized, this would also mean that even if at some point fully autonomous cars are the norm, PRT infrastructure need not be obsolete: given the absence of non-automated, 'imperfect' disturbing factors like pedestrians, non-automated vehicles, etc., average speeds in urban areas will always remain higher on a segregated track. It has been shown that under normal road conditions with many (potentially) disturbing elements, vehicle automation loses much of its potential for efficiency gains (personal communication, 2013); however, fencing off roads in urban areas will be impossible bar some selected exceptions. An elevated guideway would avoid this issue. A light elevated PRT track would be economically and socially more feasible than an elevated road. Thus, PRT infrastructure could provide a fast-track particularly in heavily congested areas where people's willingness to pay for uninterrupted travel is likely to be high. By creating long-term usefulness and systemic compatibility of PRT infrastructure with the emerging urban mobility paradigm, a major concern of investors and politicians can be resolved: that the PRT guideways could become white elephants – expensive lighthouse projects with little long-term use.

Meanwhile, PRT vehicles would always potentially remain more energy efficient than regular, even highly automated cars: being designed for higher speeds, higher acceleration and equipped with elaborate comfort and safety technology, these will remain heavier than small city vehicles or PRT pod cars. Also, due to the large amount of electronics and other luxury equipment, their embedded environmental impact would remain higher – particularly as their complexity continues to increase and high-tech components needed for automation are multiplying in number. Also, it is hard to see how the brick-wall stop requirement could be removed in a city environment due to the ubiquitous disturbing elements named before; the possibility exists for dedicated tracks though. If it were removed and sub-second headways and platooning were to become practically possible for PRT, its system capacity would rise dramatically, further improving its possible application and business case.

Thus, as opposed to being a threat to the automotive industry, quite the opposite PRT could create new opportunities of thinking of individual mobility in an urban context.

5.4 Technical compatibility

There was widespread agreement among the interviewees that car manufacturers would have the necessary know-how to build PRT systems (personal communications, 2014). Still, as one expert from VW AG research noted, while many stock car parts could be used in a PRT pod, they would typically have to be adjusted to the specific use. Others would have to be newly developed entirely. In sum he cautioned that the development costs for a good PRT system should not be underestimated, forming a reasonable barrier to entry for a car company, which would require a solid business case justify the investment (VW AG expert, personal communication, 2014). Note that this runs counter to the opinion of other interviewees and sources that an advantage of PRT is that it can use components and expertise well tested and readily available in other industries – like the automotive industry (personal communications, 2014; Carnegie & Voorhees, 2007). Likely this should be investigated case-by-case depending on the particular PRT technology.

For the convergence of PRT and other systems like automated vehicles, formidable challenges exist. For example, thinking of a hybrid or Dual Use PRT system where automated road vehicles could use PRT tracks seems intuitive but is complicated. The existing tire-based PRT systems of ULTra and 2getthere appear technically close to cars, with relatively low-tech infrastructure potentially allowing other tire-based vehicles to use the tracks as well. But, besides requiring the capacity for fully automated operation in an ecosystem like PRT infrastructure – which is arguably technically feasible already today –, these cars would also have to be compatible with the infrastructure's safety and central traffic management systems in order to allow seamless and safe operation. The vehicles' maximum dimensions and weight would equally be dictated by the PRT infrastructure.

The former is less of a technical problem but a political and economic one. While there are various national and international initiatives negotiating appropriate standards for ITS and C2X systems, these are not necessarily compatible or useful for PRT application, as noted by some interviewees (personal communications, 2014). At the same time, adjusting such standards or implementing redundant systems in cars would add cost and complexity. Conversely, if such technology were to be implemented in road vehicles, the component prices would drop drastically due to scale and could offer opportunities for cost reductions for PRT companies that are able to incorporate such standards and components in their pods.

The latter – suitability in size and weight – sounds like a minor issue but could be significant: only cars of the small dimensions of PRT pods could use its infrastructure. Otherwise, the guideways would have to grow, adding weight, size and costs and thereby nullifying its distinct advantages over other infrastructure. As the Chicago RTA/Raytheon Program taught us, this is not a wise choice. However, even the archetype of the city car, Daimler's Smart, grew to 1,66m in its current version (Daimler AG, 2014) and thus exceeds the size (though not the maximum weight) of the ULTra infrastructure (ATRA, 2014a). Whether car manufacturers would be willing to be so restrained in the design of their cars remains an open question – but since vehicles tend to grow across generations it seems unlikely unless PRT has already been deployed on a large scale, proving a compelling selling point for such compatible city vehicles. This of course is another hen-and-egg problem where infrastructure needs vehicles need infrastructure – a difficult situation to break out of.

As argued before in ***Section 4.5***, it was emphasized by nearly all interviewees that ultimately, PRT will have to evolve to be able to leave its guideways. Then, in essence PRT would become similar to CTS, whereby its infrastructure would become an optional additional selling point where it adds value – for example in highly congested or sensitive areas, or for longer distances where higher speeds make a bigger difference[6] (A. Alessandrini, personal communication, 2014). Saving on this most dominant cost factor would not only reduce PRT costs substantially, thereby increasing its economic feasibility. It would also allow greater flexibility in terms of possible applications (avoiding conflicts through visual intrusion, space requirement and facilitating integration into urban landscape) and would enhance its service value by allowing better last-mile connectivity. It would also expand the opportunities for FRT applications, allowing the automated vehicles to come much closer to – or even into – shops and businesses than would be possible if they were bound by infrastructure.

However, it should be cautioned that transferring PRT from its dedicated guideways to roads is not straightforward. For one, only tire-based PRTs qualify for this – currently the systems by ULTra and 2getthere. For another, the many advantages of the infrastructure would be lost. Moreover, technically these systems' vehicles are distinct from CTS and would not be able to navigate off track. To name but a few points, The ULTra system relies on a synchronous traffic management system and distance control embedded in the guideway, and its laser guidance system must be calibrated to the same. These systems are not applicable to and/or sufficient for navigation on open road infrastructure and if so would have to be adapted. The 2getthere system needs magnetic nails in the ground that not only would create costs and limit the range of the vehicles in an open environment but also apparently proved too sensitive to allow shared infrastructure use even in a closed system like Masdar (M. Briggs,

[6] A good example of this was given by Mr. Alessandrini: When travelling 20km (like crossing the city), a small difference in average speeds can have a large impact on your total travel times. When travelling only two kilometers however (last mile connectivity), the average speed makes a difference of only a few minutes. Thus it should be weighed carefully how large the added value of PRT infrastructure is for last mile connectivity.

personal communication, 2014). On a more mundane level, suspensions, frame and crash safety measures would have to be firmed for the uneven and 'unsafe' roads of city centers. The current PRT systems would therefore have to undergo wide-ranging changes to leave their guideways. These issues are not impossible to solve but would require substantial changes to the vehicle designs, certainly challenging these companies substantially. Partly because of such and similar constraints, some experts were skeptical about the likeliness of convergence between PRT and CTS or the automotive industry (personal communications, 2014).

5.5 Compatibility of business models

The business model of PRT is similar to that of other transit modes and thus different from the traditional one of car manufacturers that, put in a simplified way, ends once the car has been sold. Through leasing offers, company fleet programs, vehicle services and most recently car sharing programs the relevance of a vehicle to the car manufacturer is somewhat extended. Nonetheless the value added approach focuses on the vehicle, and the stakeholder network is centered on the user (VW AG expert, personal communication, 2014). Since the infrastructure is largely a public good provided by the public authorities, those costs and processes are externalized by the automotive industry, which does not have expertise in infrastructure construction and operation as required for track bound transit modes.

For PRT on the other hand, the infrastructure must be built in conjunction with the system, which means that each solution is locally specific. As we previously saw, a complex set of factors – including legal, political, geographical and even personal – need to be considered in each application, requiring extensive specific design work and negotiations. This means for one that scaling PRT systems is more difficult and slower than scaling car sales, which can be considered a major drawback of PRT (T. Sauter-Servaes, personal communication, 2014). Also, as pointed out by one interviewee, this changes the way risk and development costs are distributed. Since there are fewer projects of large volume with high complexity and political dependencies, risks are comparatively high and development costs are more difficult to off-set (VW AG expert, personal communication, 2014).

Also, car companies do not have experience with and institutional capacity for transport infrastructure projects, the complex, locally differentiated stakeholder network that for example light rail system providers have. As one VW AG expert pointed out, it is a different market with a different competitive structure and corporate institutional capacities that do not match those of car manufacturers (personal communication, 2014).

All of these increase the risk, or at least risk perception, for the car manufacturers to get involved in PRT. Particularly the infrastructure creates barriers: one could think that since automation is already and rapidly developing even towards fully autonomous vehicles, why invest in building up competencies for a technology that requires infrastructure? (VW AG expert; T. Sauter-Servaes, personal communications, 2014). It was argued in previous sections that this need not be a problem. Also being skeptical about the potential of automated vehicles to solve our mobility problems even after their market entrance around 2030, another interviewee expressed concerns about such reasoning. He cautioned that this one technology should not prevent us from searching for other options (I. Andreasson, personal communication, 2014). He is not alone with this opinion, as others warn that vehicle automation is not the holy grail of sustainable mobility and could indeed aggravate existing problems (Brustein, 2014).

The customers of PRT are also different ones than those of cars: Even though the share of fleet vehicles has been rising continuously in the traditional markets of the car manufacturers and cars are not necessarily privately owned anymore, cars are sold through emotional sales strategies. These allow for high profit margins, which do not come from the basic equipment but the luxurious or comfort promising, often irrational add-ons. This is somewhat different in the case of producers of utility vehicles like Volkswagen Nutzfahrzeuge and bus producers like Scania where the focus is more on total cost of ownership, longevity and practicality. PRT customers on the other hand are not its users but the commercial or public actor (airports, cities, universities…) purchasing the system. The sales strategy is therefore another one, since transit has not traditionally been marketed as an aspirational product.

On the other hand, maybe it is exactly here where the automotive industry could add the largest value in PRT: After all, the 'personal' in this transit mode is one of its strong suits that sets it apart from conventional transit. As both numerous studies and the expert interviews conducted here showed, riding PRT is a great experience. This potential could be leveraged in a similar fashion to the way cars are sold, making PRT not only good but great. This can be expected to make a big difference in how the concept can sell and thus succeed and scale, thereby in turn becoming more interesting for a car manufacturer to get involved.

The distinction in market approach between private and public transport may change anyway with the spread of automation and car sharing. Could a fully autonomous car still be sold through emotional selling points like driving pleasure? Who would own a fully autonomous car – what is the motivation to own it oneself rather than using one of a shared vehicle fleet, like envisioned by Google? A kind of car sharing fleet of autonomous taxis ('robotaxis') could be a solution to future urban mobility (Mui, 2014). Then, a new business case in providing such fleets would emerge where cars are offered as mobility services much like PT or car sharing are offered today. This would dramatically alter the business and ownership models of the car in urban settings, where it changes from being an aspirational product to commodity product, from private to shared – making the business model more similar to that of PRT. Marketing highly automated and autonomous vehicles or PRT could thus become similar. Such a change is not unlikely: Already today, in large cities many people only want to use, not own a car.

It is important to note that the business model behind modern car sharing schemes is not limited to the actual car rental. Beyond the revenues from the actual mobility provided, the operators of such systems also gain valuable data on the mobility patterns and usage. These are useful to optimize their offer in terms of cost and efficiency and use it for market research and branding purposes. In future, such data could also be a valuable commodity to be sold for example to real estate firms and local shops, as well as to cities for urban policy improvements – much like Google, Facebook and Amazon do already digitally. Such revenue sources could become very significant in the context of 'smart' urban mobility. These points apply equally to PRT, opening a new space for discussing value added approaches.

In order to increase the possible revenues of PRT to an acceptable level, thus making it economically more interesting for potential investors and partners in the automotive industry, various potential revenue streams exist already now as previously shown in ***Section 4.3***, ***Figure 8*** to ***Figure 10***. Where direct monetization is not possible, appropriate contracts can still help engage interested parties like real estate agents, commerce and local PT companies to share intangible costs and benefits. To reduce risks for investors and public actors as called for by the CityMobil study (2011), PRT companies could offer Performance Based Contracting. This approach couples economic gains from investments with previously agreed upon performance indicators that are periodically measured upon commencement of service. Such approaches would demand elaborate contracts and therefore detailed negotiations, which may be challenging for the relatively small PRT companies. Gaining backing of a committed champion with the needed capacity – such as the Volkswagen Group – would be of large use at this point.

This shows in brief how the traditional business model and ownership model of the automotive industry may change in the coming years due to current developments. In the past, changes to the business environment of this industry were marginal, allowing for very conservative, second-mover strategies to be very successful. As argued by Hannan and Freeman in their seminal paper on corporate inertia (1984), this is only natural and in fact an evolutionary principle of organizations in societies. However, if the ecosystem of such corporations changes more dramatically, these companies can fail quickly and dramatically if they are not able (or willing) to adapt rapidly to the new conditions (Hannan & Freeman, 1984). Recent testimonies to the power of this hypothesis include Nokia and Blackberry, which failed to react to changes quickly enough.

Like the opening quote by Mr. Winterkorn shows, clearly the automotive industry is very aware of this. Now it is time to act upon it. As all experts from the VW AG (corporate and Scania) remarked, the self-image of the company should change towards that of a mobility provider in a wider sense (personal communications, 2014). Thus, it seems as if options like PRT are becoming feasible for Volkswagen if there is an opportunity for acceptable profit margins (and other benefits). As reasoned in this chapter, this could for example be realized by means of a Dual Use PRT or in symbiosis with the MicroCity.

5.6 Summary: PRT – an opportunity for the automotive industry?

While it became clear in ***Chapters 3*** to ***5*** that PRT is unlikely to pose a threat to the business model of the car industry in urban mobility markets in the medium to long term, in principle it does fit the trend for car-free cities on the one hand and for vehicle automation on the other. A car manufacturer like Volkswagen could be the champion needed by PRT to reach mass market. Then, not only could PRT be an opportunity for the car manufacturer to offer solutions in a sustainable urban mobility paradigm. Also, systemic convergence between PRT, CTS and city cars are thinkable and could create entirely novel mobility offers with benefits for all sides. A Dual Use PRT concept and the technology's integration in a MicroCity as envisioned by the Volkswagen Group Corporate Foresight department were discussed in somewhat greater detail, showing the substantial mutual benefits for the car manufacturer and PRT.

However, the technical and organizational integration of the systems contain significant obstacles that are challenging and require extensive coordination and political will. Some options are more easily implemented than others and could be phased in step by step. Also, although PRT business model and value added networks are different from those traditionally applied in the automotive industry, the changes taking place here now and in future move them closer together. Thus PRT could become compatible with the automotive industry in terms of business model in the coming years. Even without getting involved in PRT immediately, car companies could foster the diffusion of the technology to benefit through indirect effects. Overall, conceptually the technology could be a promising option for a car company to pursue; naturally, any involvement would have to be evaluated in more detail. What is clear is that it is indeed time for the automotive industry to take the head out of the sand and consider truly innovative approaches to personal mobility in earnest; PRT could provide it with a viable option.

6. Discussion

Before concluding, the following pages are reflecting on the research process as well as further points in the context of PRT and the potential role of the automotive industry in it.

6.2 The Research process

It was the aim of RQ1 to give insights into PRT beyond those sources readily and publicly available online. Unfortunately it turned out that little information on current developments in the PRT industry appears to be available even to the interviewed experts. Thus the depth of this part of the thesis is less than satisfactory. Interviewing employees of the PRT system providers might have yielded more interesting results. Nonetheless, a comprehensive overview of the activities on PRT of the recent years could not be found during the research for this thesis, such that it still adds value.

Choosing the PESTLE heuristic for structuring the analysis (RQ2) was helpful but also highlighted the limits to the usefulness of setting such artificial boundaries. The factors found in the different categories were shown to interact heavily to a point where untangling them becomes futile.

The quantitative analysis added some value by structuring the qualitative part of the analysis, as well as allowing for a way of weighing the relative importance of the factors. However, it quickly became clear that in this form the quantitative information was merely indicative of the underlying facts. A more advanced analysis of the factor relations would yield more results. This could be done in another study with a larger sample of respondents and more structured interviews.

Many valuable angles of analysis are possible (engineering; conceptual; city planning; policy issue; sociological; etc.) and their usefulness depends on the interests of the audience. While it would be bold to claim an exhaustive review of the body of knowledge on the technology, it can be said that the vast majority of up-to-date and thus relevant sources was sighted and used for the composing of this thesis. The author hopes that with his choice of approach he was able to both add to the academic debate around PRT and to create useful information for practitioners interested in its feasibility.

Discussing potential forms of evolution of PRT and possible symbioses with the automotive industry (RQ3) with the interviewees and other people was inspiring and led to interesting results. Of course this discussion is inherently hypothetical and can merely open a frame of reference for the reader.

It also became clear that, like for any innovative technology, evaluating PRT is highly dependent on the particular characteristics of the system under scrutiny. As the literature showed, previous system designs failed for their own particular reasons. Differences between theory and practice, but also between different systems can be fundamental. Often it is subtle and/or intangible details that are all the more crucial. This makes an evaluation rather difficult and transferring of results even more so, which is why it is recommended to be cautious when generalizing from one specific case to the technological concept as a whole. The system by far most thoroughly assessed in real life is that of ULTra. Due to the absence of (reliable) information on most other systems, this type of PRT is therefore used often in this paper's analysis. The reader should keep this in mind.

6.3 Further reflections

One learning from the research process is that PRT consistently inspires people to imagine more or less futuristic options to enhance transportation functions. In this it functions like a canvas. Many more fascinating options could be explored that could lift transit to an entirely new level, approaching the comfort and convenience of a car (like personalized interiors through smartphone-based passenger profiles; here for example organic LED (OLED) walls could change color according to preference, passengers cloud music accounts could be linked into the audio system of the pod, etc.).

Like any mobility system, PRT needs to be considered in context. For one, no matter how appealing the concept appears in itself, its value will always depend heavily on the local systems it is embedded in. For example, whether infrastructure and institutions for other transit systems are already in place or not is decisive both for its political and economic feasibility and its relative environmental impacts. How well it can contribute to aspects of sustainable mobility will further depend on other policies (some talk of an integrated policy mix). To use a common phrase: PRT is not a panacea.

Moreover, particularly applied at airports and malls it at least deserves second thought whether it can be called a 'sustainable' form of mobility here at all, increasing the appeal of inherently unsustainable lifestyles (aviation and the consumer society). Likewise, PRT as a P&R application could support car ownership, which may not be in the goal of transport planners. Thus precise definitions are needed of what is meant by 'sustainable' mobility in each case, which goals PRT is intended to reach and how it fares regarding these goals in a given context.

Generally, the increasing automation of more and more realms of life raises many new questions. For example, what will the impact of increased automation be on people? If we yield more and more control to a self-driving vehicle, why should we remain able to drive a car ourselves? Will we be allowed to? After all, automated vehicles are much safer drivers than humans. Thus our perception of what is 'safe' will likely change with spreading automation. Also, what will be the impact on our sense of orientation? Already now, some neuroscientists are warning that our dependency on smartphone and car navigation systems is negatively impacting our sense of orientation (The Telegraph, 2011). Likewise, our relationship with our physical environment and our perception of reality may be altered, changing our arts and culture.[7] These are but a few reminders that, as proponents of social constructivist theories of technology such as SCOT postulate, technology develops in bi-directional interaction with social forces. Thus a normative stance is of utmost importance to shape the technology fitting our vision of society. Unchecked, it may happen the other way around.

One important but often avoided question is that of resilience. If in future generations we have lost the skill to drive and orient ourselves without electronic support, if our transport systems are highly optimized through advanced computing – what would the impact be in case of a widespread failure of these electronic systems? Without meaning to paint a

[7] This humorous web comic expresses this development quite well: http://poorlydrawnlines.com/comic/roads/

doomsday picture here, such scenarios should not be ignored. As a 2010 study commissioned by the German Bundestag found, already today our societies would collapse within few weeks without electricity (TAB, 2010). Making also our transportation fully dependent on the one resource electricity could increase this vulnerability even more.

Besides such rather extreme questions it remains to be seen how large the benefits from increased automation of transport will be. As the head scientist of Toyota cautions, the time saving, efficiency gains and raised convenience of automated driving might not help save resources, but quite the opposite incite increased car use again. Then, the recent trend of increasing bikeability and walkability of cities could be reversed and further suburban sprawl be the result (Brustein, 2014). His argument is in line with the Marchetti's constant, which holds that throughout human history, people appear to have had a rather stable 'travel budget' of about one hour per day; improvements in travel speed and quality are always compensated by more and farther journeys (Marchetti, 1994). If this rebound-effect holds true, the efficiency gains by improving personal urban mobility through automation would be largely off-set. Contributions to solving sustainability challenges e.g. of congestion, climate change and resource consumption would be marginal at best. Of course, still safety and comfort would increase in the course of this.

This once more highlights the complexity and fundamentally normative nature of technological progress. The larger picture and ultimate goals of these advancements must be defined well and kept in mind, such as more livable, safer cities and reduced resource consumption. Technologies, be it PRT, vehicle automation or others, can only be part of the puzzle leading to this goal. Their impacts should be considered carefully so they can be embedded in a system that creates the benefits we want from them. More elaborate arguments worth considering to this end are for example architect Jan Gehl's "Cities for people" (2010) or James Howard Kunstner's critique of the "Geography of Nowhere" (1993).

The research process for this thesis, by its very nature challenging at times, was also a process of learning regarding some of the processes involved in technology development. The unequivocal openness of the interviewees to dedicate their time and expertise to contribute to this thesis was as uplifting as it was somewhat unexpected given the senior positions many of them occupy. The value of the many talks and discussions led not only with the interviewees but also colleagues, family and friends – often critical but always constructive and very engaged –, cannot be overstated.

Not all goals of the thesis were reached: The initial planning with the Volkswagen Group department of Corporate Foresight had been to do an initial assessment of the suitability of PRT for the company's home plant and the attached city Wolfsburg, Germany. Due to time constraints, timing (summer holidays) and other contextual factors this was not possible in the three months with Volkswagen. However, it was very gratifying to see that through the research process of this thesis some key persons – from Volkswagen as well as from another private German institution – became curious enough about the capabilities of PRT to give it serious consideration for an implementation. While it is entirely open what the results of these first thoughts will be, these developments by themselves are more than could reasonably be hoped for.

7. Conclusions

This thesis gave an up-to-date review of Personal Rapid Transit (RQ1). The premise of the investigation was that PRT appears suitable to the given context a changing global urban mobility paradigm.

Since 2010, the three first 'true' PRT systems have launched, each following rather distinct designs and provided by very different suppliers. Due to their small size, these three projects were not able to demonstrate the feasibility of the concept in a full-scale network where its advantages are hypothesized to be the largest. Even though PRT was evaluated superior to other modes of transit for low- to medium density cities, urban applications are still amiss. A promising project in Amritsar, India has stalled if not failed. As of 2014, there are four PRT system and management suppliers active globally. The market remains nascent, with few activities to be noted recently and no concrete new projects under progress. For the medium term, diffusion of PRT will be limited and thus its overall impacts on urban mobility likely negligible. Nonetheless, it appears that interest in PRT is starting to increase again, and the proposal of the concept is more appealing than ever.

By means of expert interviews, the current drivers and hurdles to the concept were investigated and compared to those identified in previous literature (RQ2). It appears that the – only partly proven – conceptual strengths of PRT as well as its comparatively low costs are key drivers. On the other hand, a complex mix of political and economic factors strongly inhibits the progress of the technology. Many of these relate to perceived or actual risks due to the lack of a full-scale demonstrator, the political context, expected lack of social acceptance, and the difficulty to monetize the benefits of the concept for private profits. The segregated infrastructure needed for PRT, while allowing for it to implement 'low-tech' automation already today, is the cause of many of these issues. In order to advance PRT, a champion is needed that is willing to commit to a larger-scale application that proves the system's capabilities in a network – ideally in an urban setting. More industry standards would be useful to streamline project processes. Additionally, it would be a great advantage if PRT could evolve to be less dependent on its infrastructure.

Thirdly, based on the results of the first two research questions, potential interactions between PRT and the automotive industry were critically discussed (RQ3). It was argued that a range of options are thinkable that would create mutual benefits. The technical feasibility and economic attractiveness of each of these options would have to be assessed in more detail. While some interactions would be possible without many difficulties, others would require significant dedication of both the PRT supplier and the automotive manufacturer engaging in it. Overall it was concluded that PRT is conceptually suitable for the automotive industry in this current context of challenges to its traditional business environment and should be considered carefully as a potential option for future business.

Further research is needed on PRT, of both conceptual and applied nature.

Some technical problems of PRT still need solving on theoretical or practical level, like advancing asynchronous vehicle management, station management, ride sharing, integration and interaction with other policies and measures for sustainable transportation. While the theoretical progress in these is important, their feasibility will be largely dependent on each distinct PRT design where real life implementation and demonstration will be crucial.

More conceptual work is needed for Dual Use PRT systems and FRT. Considering the former in conjunction with CTS and city cars and the latter with novel logistics concepts would be useful. Detailed technical studies into each of these are needed before more inferences regarding their feasibility can be made. For further development of ATS overall, developing new options for in-drive customer entertainment, vehicle personalization and/or in-vehicle advertisements could be useful.

More comparative policy analyses would be useful of PRT, other ATS and conventional modes of transit in terms of their effectiveness towards different policy goals (congestion relief, improving air- and noise pollution, energy efficiency, etc.). Particularly a thorough analysis of the suitability of PRT for addressing express goals of European and national climate and urban transport policies would be valuable to discern whether additional public support of the technology would be warranted.

Concluding, it can be said that PRT may be at a crossroads. If it were to remain in its current form, it may become obsolete before scaling due to the fast advances in vehicle automation and ICT. If, however, it is possible to evolve the concept – ideally in cooperation with a champion like for example the automotive industry– PRT might indeed be an urban mobility mode of the future.

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Appendix

Appendix A. Guiding Questions internal (English)

Thesis: expert interview guiding questions

1. Are you familiar with the concept of Personal Rapid Transit (PRT)?

2. If so, are you involved in PRT (directly or indirectly)? How?

(If you do not know PRT, please read the short description below)

3. Do you have projects that are related to PRT?
    a. Do you or someone in your department have qualifications that could be relevant to PRT?
    b. Could you name persons (please include department) within the Volkswagen corporation which work on PRT-related project or have applicable qualifications?

4. How do you evaluate PRT regarding its effectiveness to address issues of urban mobility?

5. How do you evaluate the opportunities for market growth in PRT in the coming 10 years?

6. How do you evaluate the overall potential impact of PRT on urban mobility markets in Europe?

7. According to your experience with PRT projects (if applicable; otherwise according to your knowledge), please identify central
    a. Drivers
    b. Restraints
    c. Reasons for success / failure
    d. Additional relevant experiences

8. Which parameter (political, economic, cultural, technical, social, etc.) would have to change to foster the diffusion of PRT systems?

9. Could you imagine that Volkswagen AG gets engaged in the field of PRT?
    a. No: Why not? Under which circumstances?
    b. Yes: Which unit of Volkswagen AG?
    c. Why?

10. Further comments

PRT short description

Rapid Transit (PRT) is a system of automated, electric, small capsules (so-called 'pods') for 2-6 passengers that run on segregated guideways. Stations are set off the main line, providing for non-stop journeys and thus, for urban transport, very high average speeds. Theoretical advantages of PRT include higher energy efficiency per passenger kilometer and higher travel speeds than a comparable tram system, while having lower capital costs than the same and allowing for profitable operation. Social benefit-cost analyses are consistently favorable of PRT due to expected time savings and low costs for operation. These advantages have been confirmed both in practical pilot projects and several extensive EU funded research studies (like EDICT, 2005 and CityMobil, 2011).

Appendix B. Guiding Questions external (English)

Thesis: expert interview guiding questions

1. What is your position / job description?

2. Are you familiar with the concept of Personal Rapid Transit (PRT)?

3. If so, are you involved in PRT (directly or indirectly)? How?

   (If you do not know PRT, please read the short description below)

4. How do you evaluate PRT regarding its effectiveness to address issues of urban mobility?

5. How do you evaluate the opportunities for market growth in PRT in the coming 10 years?

6. How do you evaluate the overall potential impact of PRT on urban mobility markets in Europe?

7. According to your experience with PRT projects (if applicable; otherwise according to your knowledge), please identify central
   a. Drivers
   b. Restraints
   c. Reasons for success / failure
   d. Additional relevant experiences

8. Which parameter (political, economic, cultural, technical, social, etc.) would have to change to foster the diffusion of PRT systems?

9. Which are currently the central players in the PRT markets?

10. For which market participants do you see opportunities to get involved in PRT, and in which areas?

Potential market participants	**Potential areas of involvement**
IT Companies, e.g. Google, IBM	Pod-car construction
Car manufacturers, e.g. Volkswagen, BMW	Electronics, sensors
Suppliers, e.g. Bosch …	Software
Infrastructure operators, e.g. Parking- Traffic management companies	Infrastructure construction
Other	Operation
	Other

11. Do you see efforts of the market participants above to get involved in PRT?

12. Further comments

PRT short description

Rapid Transit (PRT) is a system of automated, electric, small capsules (so-called 'pods') for 2-6 passengers that run on segregated guideways. Stations are set off the main line, providing for non-stop journeys and thus, for urban transport, very high average speeds. Theoretical advantages of PRT include higher energy efficiency per passenger kilometer and higher travel speeds than a comparable tram system, while having lower capital costs than the same and allowing for profitable operation. Social benefit-cost analyses are consistently favorable of PRT due to expected time savings and low costs for operation. These advantages have been confirmed both in practical pilot projects and several extensive EU funded research studies (like EDICT, 2005 and CityMobil, 2011).

Appendix C. Relations matrix: Drivers

Relations Matrix: Drivers	Political	Supportive political climate	Economic	Business case	Comparatively low costs	Available funding	Socio-cultural	Appealing concept	Innovation acceptance	Accessibility	Fitting cultural / public discourse	Psychological empowerment	Technological	High speeds	Non-stop service	Capacity enough for Low-med density	Convenience	Better than conventional transit	Compatibility with automation trend	Addresses congestion	Proven reliability & safety	Improves existing transit	Low space requirements	"Low-tech" automation	Unique capabilities	Good in network & for last-mile connectivity	On-demand	Space requirement	Legal	Safety certification relatively easy	Environmental	Environmental performance	Silent	Electric	Energy efficiency	PESTLE relations	PRT component	Pod cars	Infrastructure	system management	Vehicle automation	Total relations
Political																																										
Supportive political climate				1	1	1			1	1	4					1			5	1	1	1		1						2					1	22						22
Economic																																				0						0
Business case		1			1						1								3																	6			1			7
Comparatively low costs		1		1				1		1				2		4	2		2	1	2	1	1	1	4	2	3						1		2	32			2		1	35
Available funding		1																																		1						1
Socio-cultural																																				0						0
Appealing concept					1						1	1		1		1	4	1	1		2				2	2	3						1		1	22						22
Innovation acceptance		1									2			1			1									1	2									8						8
Accessibility		1			1									1	1	2	1			1		2			1	1	2								1	15						15
Fitting cultural / public discourse		4		1				1	2								1		2								1					1				13						13
Psychological empowerment								1										1									1									3						3
Technological																																				0						0
High speeds					2			1	1	1							2				1				2	2	2									14			1			15
Non-stop service										1							1								1		1									4						4
Capacity enough for Low-med density		1			4			1		2							1		1	3	1	2	1		4	1	2	1				3	1		2	31			1		1	33
Convenience					2			4	1	1	1			2	1	1					5				5	2	5						1		1	32						32
Better than conventional transit								1				1															1									3						3
Compatibility with automation trend		5		3	2			1			2					1					2			4	1					2					1	24						24
Addresses congestion		1			1					1						3						2	2	1	2			1				5			1	20			2			22
Proven reliability & safety		1			2			2						1		1	5		2					2	4	1	1			3			1		2	28						28
Improves existing transit		1			1					2						2				2					1	1						1			1	12			1			13
Low space requirements					1											1				2				2	1			1		1		1				10			3			13
"Low-tech" automation		1			1														2	1	2		2		1					2					1	13			3			16
Unique capabilities					4			2		1				2	1	4	5		1	2	4	1	1	1		2	4	1				2	1		4	43			2			45
Good in network & for last-mile					2			2	1	1				2		1	2				1	1			2		3						1		1	20						20
On-demand					3			3	2	2	1	1		2	1	2	5	1			1				4	3							1		2	34						34
Space requirement																1				1			1		1							1				5			1			6
Legal																																				0						0
Safety certification relatively easy		2																	2		3		1	2												10			1			11
Environmental																																				0						0
Environmental performance											1					3				5		1	1		2			1					1	1	1	17			1			18
Silent					1			1								1	1				1				1	1	1					1			2	11						11
Electric																																1				1						1
Energy efficiency		1			2			1		1						2	1		1	1	2	1		1	4	1	2					1	2			24						24
PRT component																																										
Pod cars																																				0						
Infrastructure				1	2									1		1				2		1	3	3	2			1		1		1				19						
System management																																				0						
Vehicle automation					1											1																				2						

Subtotal relations

499

Appendix D. Relations matrix: Hurdles

Relations Matrix: Hurdles	Political	Lack of market, competition	Public funding requirements	Process Complexity & slowness	Risk aversity of public actors	Lacking demonstrators: credibility	Lacking understanding/expertise of 3rd parties	Political volatility	High political risk	Economic	Lack of business case	Lacking economies of scale	Lack of funding	Limited capacity of of PRT companies	Capital costs	Economic risk	Socio-cultural	Cultural change needed	Accessibility	Low innovation acceptance	Low public acceptance - visual intrusion	Technological	variety of PRT systems	Complexity	System complexity limited	Inflexible	Conflict with existing infrastructure & systems	Technologically obsolete	Space requirement	Capacity limitation	Lacking compatibility with existing systems	Legal	administrative burden	Certification & standardization	Legality	Environmental	Environmental Footprint	PESTLE relations	PRT component	Pod cars	Infrastructure	System management	Vehicle automation	Total relations
Political																																												
Lack of market, competition			3			1							2										1											2				9			1			10
Public funding requirements		3		2	1	2		3			3	2	3		2	1							1											3	1			27			3			30
Process Complexity & slowness			2		1	3		6	2		3	5	1	2	4	3				1	1		1	4									2	3	2			46		1	9			56
Risk aversity of public actors			1	1		1		2	4		3		4	1	4			2		3	1						1	1		2	2							33			5			38
Lacking demonstrators: credibility		1	2	3	1		2		3		2		2	3	3	2		1		1			1	2						3	1			3				36			3			39
Lacking understanding/expertise of 3rd						2			1		2			1	1	2		1						1						1			1		1			14						14
Political volatility			3	6	2				1		2	3			2	2				1	1												1		1			25			5			30
High political risk				2	4	3	1	1			1		1	1	5	3				2	3		1	1			2						2					33			10			43
Economic																																						0						0
Lack of business case			3	3	3	2	2	2	1			1	2	1	3	2		1										1			1		1	1	1			31			6			37
Lacking economies of scale			2	5				3			1				3	2		1		1				1							1		1	1	1			23		1	4			28
Lack of funding		2	3	1	4	2			1		2			1	2	1				1			1				2		1		1			2				27			5			32
Limited capacity of of PRT companies				2	1	3	1		1		1		1		1												1	1		1	1			1				16			1			17
Capital costs			2	4	4	3	1	2	5		3	3	2	1		1		1	1		3		1	5		2	3		2		1		1	2	1		1	55		2	25			82
Economic risk			1	3		2	2	2	5		2	2	1		1					1			1	1							1		2		2			29			2			31
Socio-cultural																																						0						
Cultural change needed					2	1	1				1	1			1					3							2	1			3							16			1			17
Accessibility															1														1									2			1			3
Low innovation acceptance				1	3	1		1	2			1	1			1		3			1		1	1			1				1							19			1			20
Low public acceptance - visual intrusion				1	1			1	3						3					1							6		2		1				2			21			13			34
Technological																																						0						
Variety of PRT systems		1	1	1		1			1				1		1	1				1				2						1				2				14			1			15
Complexity				4		2	1		1			1			5	1				1			2			1			1	1			1	2				24		1	6			31
System complexity limited																																						0				2		2
Inflexible															2									1					1									4			5			9
Conflict with existing infrastructure & systems					1				2				2	1	3			2		1	6							1	5		3						1	28			17			45
Technologically obsolete					1						1			1				1									1				4							9			4			13
Space requirement													1		2				1		2			1		1	5											13			9			22
Capacity limitation					2	3	1							1									1	1							1						1	11			3			14
Lacking compatibility with existing systems					2	1					1	1	1	1	1	1		3		1	1						3	4		1								22			4			26
Legal																																						0						
Administrative burden				2			1	1	2		1	1			1	2								1										1	1			14		1	2			17
Certification & standardization		2	3	3		3					1	1	2	1	2								2	2									1		2			25		1	1			27
Legality			1	2			1	1			1	1			1	2					2												1	2				15			2	1		18
Environmental																																						0						
Environmental Footprint															1												1			1								3			3			6
PRT component																																												
Pod cars				1								1			2									1									1	1				7						
Infrastructure		1	3	9	5	3		5	10		6	4	5	1	25	2		1	1	1	13		1	6		5	17	4	9	3	4		2	1	2		3	152						
system management																									2										1			3						
Vehicle automation																																						0						

Subtotal relations 806