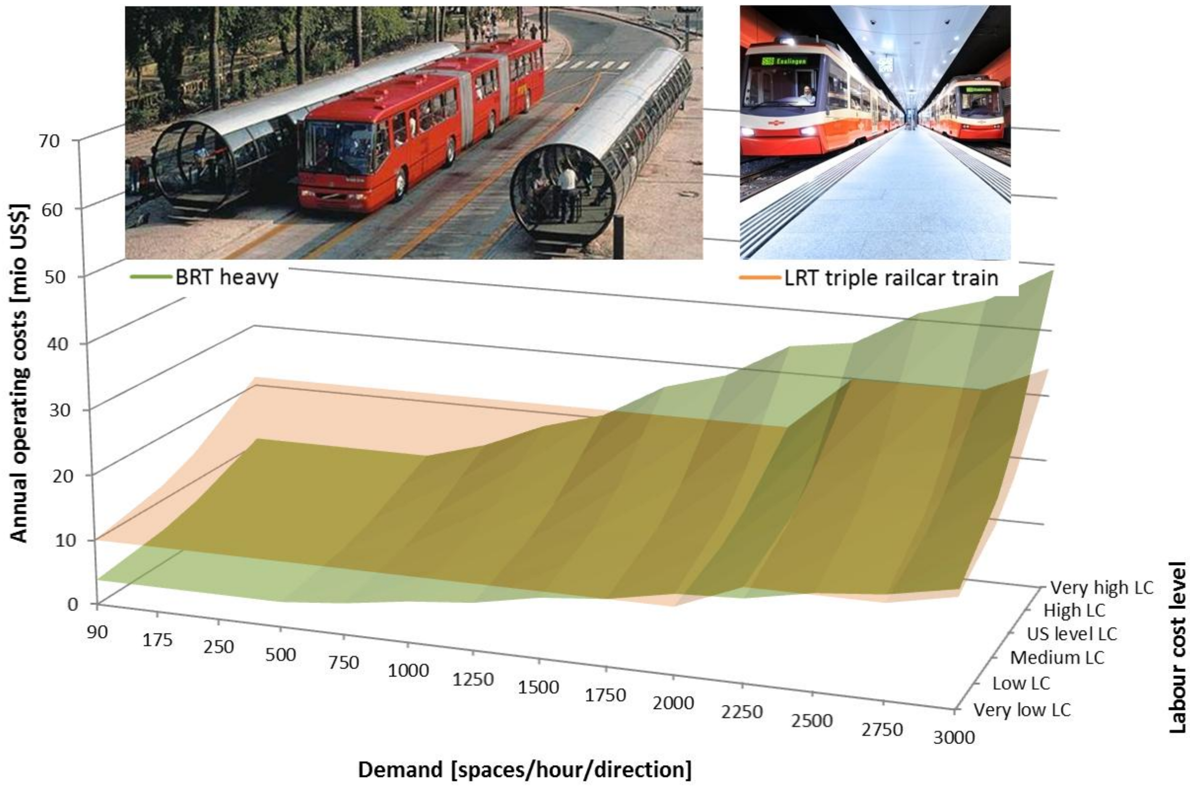


Bus rapid transit systems and beyond

Exploring the limits of a popular and rapidly growing urban transport system

David Sorg

Advising Professor: Prof. Dr. Ulrich Weidmann, IVT ETH Zürich

Supervisor: MSc ETH SD&IS Nelson Carrasco, IVT ETH Zürich

Master Thesis

MSc in Spatial Development and Infrastructure Systems **July 2011**

Institut für Verkehrsplanung und Transportsysteme
Institute for Transport Planning and Systems

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Acknowledgements

I want to thank the following persons for their highly appreciated contributions and inputs. This work would not have been possible without their valuable support.

Prof. Dr. U. Weidmann and Nelson Carrasco benevolently accepted to supervise this master thesis and assumed this task with great enthusiasm and commitment. Their constant and competent support, feedbacks, suggestions, and critique vitally contributed to guide and improve this work.

Nicolas Leyva, Wolfgang Forderer, and Patrick Daude from the network 'cities for mobility' in Stuttgart helped to develop the idea of this work. Their interest in the findings and results greatly contributed to the motivation and impetus that guided this work.

Rebecca Bechstein, Flurin Feldmann, Gerold Signer, and Reto Rieder made crucial contributions to the quality of this work by their patient and persistent support in proofreading, commenting, and correcting. In exchange, they are experts in BRT systems by now.

Finally, my family and close friends always provided invaluable support, backing, and motivation during my entire studies. Without their help, all this would not have been possible.

References for the images on the title page: URL (2011a, b)

Table of contents

List of tables

List of figures

Abbreviations

BHLS	Buses with a high level of service
BRT	Bus rapid transit
CA	Cluster average
CfM	Cities for Mobility, the Stuttgart-based worldwide network for urban mobility
HOV	High occupancy vehicle
ITS	Intelligent transport systems
LRT	Light rail transit
PPP	Purchasing power parity
PT	Public transport
RIT	Rede Integrada de Transporte (the BRT system in Curitiba, Brazil)
ROW	Right of way
s/h/d	Spaces per hour per direction

Master Thesis, MSc Program in Spatial Development and Infrastructure Systems

Bus rapid transit systems and beyond: exploring the limits of a popular and rapidly growing urban transport system

David Sorg
Wehntalerstrasse 35
8057 Zürich

Telephone: +41 79 798 83 67
E-Mail: dsorg@student.ethz.ch

July 2011

Abstract

In the last decade, the world has seen a massive growth in the number of bus rapid transit systems (BRT). This growth was sparked off by the successful implementation of the first BRT system in Curitiba (Brazil) in the 1970s. BRT aims at providing cost-effective urban transport at a high quality of service, and it doubtlessly is a step ahead in the quest for affordable and improved urban public transport. However, rail-based systems are still a valid alternative for situations in which the limits of BRT systems are reached. Therefore, a main objective of this master thesis is to explore the limitations of BRT systems in urban areas. For this purpose, this work analyses the performance of different BRT systems regarding quality of service, capacity, and cost-efficiency. Threshold levels in passenger demand for choosing between modes are identified by means of a parametric cost model. Findings indicate that BRT has cost and quality advantages over conventional bus and light rail transit (LRT) operation at demand levels between ca. 250 and 2000 spaces per hour per direction. BRT proves to be especially favourable compared to LRT in situations where labour costs are low, where a high commercial speed can be achieved, where frequent services are desired, and where high vehicle load factors are tolerated. Empirical data show that in comparison to conventional bus systems, BRT offers particular quality advantages regarding capacity, accessibility, comfort, safety, and image.

Keywords

Bus rapid transit systems (BRT); threshold passenger demand levels for mode choice; quality of service; capacity; cost-efficiency; parametric cost model; commercial speed; reliability.

Preferred citation style

Sorg, D. (2011) Bus rapid transit systems and beyond, *Master Thesis*, IVT, ETH Zürich, Zürich.

Deutsche Zusammenfassung

Im Lauf des letzten Jahrzehnts hat die Zahl von Bus Rapid Transit Systemen (BRT) weltweit massiv zugenommen und umfasst inzwischen mehr als 120 Systeme des öffentlichen Personennahverkehrs auf sechs Kontinenten. Diese Entwicklung wurde massgeblich durch die Entwicklung eines damals neuartigen Bussystems in Curitiba (Brasilien) in den 1970er Jahren ausgelöst, welches bereits diverse Charakteristiken von heutigen BRT Systemen vorwegnahm. Das Konzept von BRT besteht darin, qualitativ verbesserte Bussysteme mit einer erhöhten Kapazität als leistungsfähige, kostengünstige, rasch umsetzbare und effiziente städtische Verkehrssysteme einzusetzen, und diesen die verkehrlichen Funktionen zuzuweisen, die traditionell von Schienenverkehrssystemen oder herkömmlichen Bussystemen eingenommen wurden. BRT Systeme zeichnen sich insbesondere durch neuartige Fahrzeuge und Haltepunkte, exklusive Fahrwege, Fahrzeugbevorzugungsmassnahmen, Leitsysteme, zeitgemässe Betriebskonzepte, eine hohe Taktdichte, moderne Bezahlungsmethoden und Tarifsysteme, hochstehende Informationsdienstleistungen, sowie durch ein sichtbares Marketing und Identifikationsmerkmale aus. Die Popularität des Ansatzes lässt keinen Zweifel daran, dass BRT in vielen Fällen verbesserte und bezahlbare Lösungen im öffentlichen Stadtverkehr ermöglicht hat, und ein Ende des weltweiten Siegeszuges ist noch nicht abzusehen. Auf der anderen Seite sind schienenbasierte Stadtverkehrssysteme nach wie vor eine zweckmässige und gängige Alternative. Dies besonders in Fällen, in denen BRT Systeme an ihre Grenzen stossen. Die Planung und Implementierung von BRT Systemen wurde in der Literatur bereits umfassend ausgeführt, die Grenzen von BRT Systemen und Entscheidungskriterien für die Systemwahl zwischen BRT und Schienenverkehrssystemen wurden bisher aber erst wenig beleuchtet.

Die vorliegende Arbeit befasst sich daher insbesondere mit den Grenzen von BRT Systemen, vor allem in den Bereichen Qualität, Kapazität und Effizienz. Dazu werden BRT Systeme zunächst eingehend beleuchtet und Unterschiede zu konventionellen Bussystemen aufgezeigt. Ein neuer Klassifikationsansatz wird entwickelt, der eine objektive Identifizierung von vier verschiedenen Klassen von BRT Systemen erlaubt. Danach werden die Qualität, Leistungsfähigkeit und Effizienz dieser Systemklassen aus den Perspektiven der Benützer, Betreiber und der Öffentlichkeit analysiert. Diese Betrachtung liefert eine Basis für die Identifizierung der Grenzen von BRT Systemen und ermöglicht einen Vergleich mit modernen Stadtbahn-, Tram- und herkömmlichen Bussystemen. Danach wird ein parametrisches Kostenmodell vorgestellt, welches die Berechnung verschiedener Szenarien von jährlichen Betriebskosten verschiedener Verkehrsmittel erlaubt. Damit können Schwellenwerte für die Wahl des jeweils effizientesten Verkehrsmittels für verschiedene Nachfragestärken und Randbedingungen wie Lohnkostenniveaus, Systemgeschwindigkeit, Energiekosten und Qualitätsvorgaben ermittelt werden. Neben diesen Schwellenwerten werden Möglichkeiten und Erfolgsfaktoren für eine

weitere Verbesserung von BRT Systemen aufgezeigt. Die Resultate der Arbeit zeigen, dass die Vorteile von BRT Systemen insbesondere bei Nachfragestärken zwischen 250 und 2000 Passagieren pro Stunde pro Richtung zum Tragen kommen. Die Vorteile dieser Systeme gegenüber Stadtbahnen entfalten sich insbesondere in Situationen mit tiefen Lohnkosten, wenn eine hohe Systemgeschwindigkeit erreicht werden kann, wenn starke Fahrzeugauslastungen von den Fahrgästen akzeptiert werden, und wenn Fahrzeuge mit einer erhöhten Kapazität (z.B. Doppelgelenkbusse) eingesetzt werden können. Im Vergleich zu herkömmlichen Bussystemen erlauben BRT Systeme markante Verbesserungen in der Kapazität, Zugänglichkeit und Sicherheit, sowie hinsichtlich Komfort und Image. Ausführliche Schlüsse werden am Ende der Arbeit vorgestellt, und kurze Zusammenfassungen am Ende jedes Kapitels ermöglichen eiligen Lesern einen schnellen Überblick.

1 Introduction

In the late 1970s, the city of Curitiba (Brazil) successfully implemented a qualitatively enhanced and integrated bus-based urban transport system. The Curitiba system initiated the continuing rise of bus rapid transit (BRT) systems, and the example has since been followed by numerous cities around the globe. Especially in the last decade, the world has witnessed an explosion of the number of BRT systems. The BRT concept aims at providing customer-focused and cost-effective urban transport. Main arguments of BRT advocates are that its performance and amenity characteristics are similar to modern rail-based systems but can be obtained at much lower costs and shorter implementation times (Wright et al., 2007, p. 11). There is no doubt that BRT systems are a step ahead in the quest for providing affordable and improved urban public transport. However, the planning and implementation of new rail-based systems in cities has not come to a halt. On the contrary, rail-based systems are still a valid alternative in situations where the limits of BRT systems are reached and a system with a higher performance is required. If systems operate at the capacity limit, the quality of service often decreases, undermining the efficiency of the public investment. Therefore, an informed system planning and mode choice process requires the identification of the limitations of BRT systems, especially in terms of quality, capacity, and cost-efficiency. While there is abundant literature on BRT planning and implementation, less research has been done on its limitations and on threshold levels for choosing between modes. In recent years, there has been a growing need to extend the traditional cost-based mode comparison methodology, and aspects of the quality of service will have to be included into the evaluation to a greater extent (Vuchic, 2005, p. 525). Hidalgo et al. (2010a, p. 33) identify the need for objective analyses to identify criteria for choosing between modes since too many decisions have been made based on ideological arguments or commercial interests.

Therefore, the main purpose of this work is to explore the limitations of BRT systems in urban areas and to compare modes regarding quality of service. To address this issue, this work will develop a common understanding of the performance of urban bus services and analyse influencing factors. Firstly, the BRT mode will be presented in greater detail by analysing its origins and evolution, as well as characteristic dimensions in which this mode differs from conventional bus systems. Secondly, a classification approach will be developed, which considers the main dimensions of BRT systems by means of statistical cluster analysis. The approach is used to examine empirical data and to identify four distinct classes within the BRT spectrum. Thirdly, the different perspectives on performance by users, operators, and the community will be addressed. In particular, the quality of service, capacity, and cost-efficiency of BRT systems will be evaluated to provide a basis for the identification of limitations and the comparison to other modes. Based on this performance analysis, BRT systems will be compared to conventional bus and light rail transit (LRT) operation. A parametric cost model will be used to calculate operating cost scenarios of different modes in a model corridor. By this means, threshold levels for choosing the most cost-efficient mode for different travel demand levels will be identified. Subsequently, a conclusion will be drawn which identifies ways of improving BRT systems and detects the situations where the choice of another mode should be considered. Finally, an analysis of successful and less successful BRT examples will point out critical success factors for the implementation of BRT systems. Short review sections at the end of each chapter will be provided for speedy readers.

1.1 Objectives and tasks

In this section, the general and specific objectives, defined by the supervisors of this master thesis, will be reproduced word by word. An exact reproduction of the more detailed listing of tasks has been included in annex A 1.

1.1.1 General Objectives

- Provide a better understanding of the limitations of BRT systems in urban areas.
- Contribute to the development of a common understanding of the elements influencing the quality levels of an urban bus service.

1.1.2 Specific Objectives

- Identify the main BRT system characteristics and situations that contribute to reaching system capacity and the consequences for users and operators.
- Classify existing BRT systems according to adequate criteria (capacity, level of investment, benefit for community, quality of service, financing, urban structure, etc.)
- Analyze the reasons for success and failure of implemented BRT systems.
- Compare the quality of different BRT systems and understand the underlying reasons for providing a given LOS (planning, operational, technical, cultural differences).
- Elucidate the most influential elements for improving existing BRT system quality (user perspective) and performance (operator perspective).
- Develop a generic guide of problems and possible solutions for improving BRT systems.
- Provide an insight on the thresholds values involved in the decision between BRT and Metro systems.

1.2 Constraints

This master thesis was subject to formal constraints, as well as in data and literature availability, which will be explained below. Supervision was assumed by Prof. Dr. U. Weidmann and Nelson Carrasco. The work will be submitted to the Institute for Transport Planning and Systems (IVT) at the Swiss Federal Institute of Technology (ETH Zürich). The topic was chosen in collaboration with Cities for Mobility (CfM), a Stuttgart-based worldwide network for urban mobility. The results of this work will be presented at the CfM world congress in Stuttgart in July 2011.

1.2.1 Formal constraints

The time restriction for completing this master thesis amounted to 127 days between the kick-off meeting on Monday, 28.02.2011 and the deadline on Monday, 04.07.2011. The length of this work was limited to 120 pages without indexes and annexes.

1.2.2 Data and literature availability

This work experienced severe limitations in the quality of the available raw data. In the cases where quantitative analyses have been performed, the raw data originated mainly from Diaz et al. (2009) and Wright et al. (2007). A rough manual credibility check quarried some obvious inconsistencies in the data that may stem from the original compilation process that used various sources from all over the world. It is probable that inconsistencies partly result from local sources using inconsistent definitions and measuring units. Due to temporal constraints, it was not possible to double-check all empirical data or to collect missing values. Though, only a rough plausibility check and an according review could be performed. However, the main idea of the quantitative analyses in this work is not to provide exact values for each system, but to convey a general picture by using a wide variety of system examples. The author of this work therefore wishes to highlight that errors in the data entries cannot be excluded completely. Literature research relied on library and online research and a considerable amount of literature was provided by the supervisors. There is an abundance of literature on the BRT topic, though fewer references could be found discussing the limitations of this mode and on threshold levels for choosing between modes. In many cases, there does not seem to be a generally used terminology within the field of BRT systems. Therefore, this work uses a set of own definitions, which are listed in the glossary in chapter 9.

2 Bus rapid transit: a new transport mode?

In the late 1970s, the City of Curitiba (Brazil) witnessed a revolution of its transport system. Under the administration of Jaime Lerner, a new master plan for the city was developed and led to the implementation of the Rede Integrada de Transporte (RIT) system. This public transport system is described by Grava (2003, p. 391) as "unquestionably the strongest and most encompassing bus system anywhere in the world". The Curitiba system contains a variety of elements that distinguish it from normal bus systems. Some of its main features are exclusive busways forming an integrated network across the entire city, modern tube-shaped stations providing level access to bi-articulated vehicles, pre-board fare collection, and a distinctive marketing identity (Wright et al., 2007, p. 14). These main characteristics of the Curitiba system have since been adopted by a number of cities around the world. By the year of 2010, more than a hundred cities on six continents claim to operate a bus rapid transit (BRT) system, being an enhanced bus system with at least some (if not all) of the features of the Curitiba example (Hidalgo et al., 2010b). Of course, the number of cities that have introduced at least some basic improvements in their conventional bus systems is by far larger. So, which features are required that a transport system ceases to be a conventional bus system and starts to be a bus rapid transit system, where is the border, and is BRT really a new transport mode? Transport modes are defined in the glossary of this work (see chapter 9) as substantially different ways to perform transport, with each mode using a fundamentally different technology and requiring specific environments and infrastructures to operate. In fact, most BRT systems are distinguished from conventional bus systems by the use of specific technologies and infrastructures. The sub-category of laterally guided systems even requires a specific environment to operate – the so-called guideways. Therefore, it could be argued to identify BRT as a separate transport mode, as it is proposed by Grava (2003) and by the present work. Chapter 2.2 indicates that BRT is not a completely new concept, but incorporates the ideas of improvements in bus systems that have been developed during decades. But the question if bus rapid transit in fact is a new transport mode is finally of less importance to transport planners than the knowledge about its possibilities and limitations in comparison to other public transport solutions.

Chapter outline: the foremost objective of this chapter is to provide a better understanding of what bus rapid transit systems really are. The term of bus rapid transit will be defined and the specific dimensions of BRT systems will be explained in more detail. The origins and evolution of the BRT mode will be presented, as well as recent developments within this transport mode. Different functions of BRT systems in urban contexts will be presented alongside with the special case of bus systems with lateral guidance.

2.1 Defining BRT: what makes bus transit "rapid"?

Most passengers travelling on a modern BRT system would probably agree that their means of transport shows some differences to a commonly known standard bus system. This chapter will shed light on these differences and aims at identifying the factors that distinguish BRT systems from standard bus systems. A standard bus is defined broadly as a self-propelled, rubber-tired road vehicle designed to carry a substantial number of passengers, commonly operated on streets and highways (Kittelson & Associates Inc. et al., 2003, p. 8-6). The same authors state that bus rapid transit is an inexact term describing a bus operation providing service similar to rail transit, at a lower cost. They identify various elements to improve bus speed, reliability, and identity: exclusive transitways, enhanced stations, easily identified vehicles, high frequency all-day service plans, simple route structures, simplified fare collection, and intelligent transport system technologies (ITS) for vehicle prioritisation and operations management purposes. Another definition by Wright (2003) describes BRT as high quality, customer orientated transit that delivers fast, comfortable and cost-effective urban mobility. Levinson et al. (2003) state that BRT systems are designed to be appropriate to the market they serve and their physical surroundings, and they can be incrementally implemented in a variety of environments. The same authors provide detailed information about the different elements of BRT systems and define BRT as a flexible, rubber-tired rapid-transit mode that combines stations, vehicles, services, running ways, and ITS elements into an integrated system with a strong positive identity that evokes a unique image. They state that BRT, in many respects, is rubber-tired light-rail transit (LRT), but with a greater operating flexibility and potentially lower capital and operating costs.

To sum these definitions up, a BRT system can be distinguished from a conventional bus system by its higher quality (including speed, comfort, reliability etc.), its higher capacity, its cost-effectiveness and its positive image and integration. However, it may not always be clear where the delineation between a bus and a BRT lies. Grava (2003, p. 393) even highlights that the emergence of BRT as a new transport mode should be seen in the context of numerous bus service improvement measures that have been implemented by cities during decades. He does not see BRT as the advent of a revolutionarily new transport mode, but as the formulation of a new label for the product of continued efforts to improve conventional bus services. With a bit of sarcasm, he concludes that image counts for much in our society, and thus giving a recognizable label to worthwhile programs should help to legitimize and popularize them in the public forum.

2.1.1 The BRT definition of this work

Departing from the listings by the above authors, this work develops its own definition of bus rapid transit, which is closely related to quality of service. Both these terms are therefore defined here.

Bus rapid transit systems are qualitatively enhanced bus systems that aim at providing cost-effective urban transport with a strong customer focus, a high quality of service, a suitable capacity, and a beneficent social, economic, and environmental impact. This is achieved through a combination of high-quality vehicles, infrastructures, service and operation plans, branding elements, as well as operations management, vehicle prioritisation, and fare collection technologies, which are selected and specified individually for every implementation case, requiring well-organized and integrated planning.

Quality of service is the overall measured or perceived performance of transit service from the passenger's point of view, in terms of availability, accessibility, travel time, reliability, user cost, comfort, safety, security, image, customer care, and environmental impact (based on Kittelson & Associates Inc. (2003 p. 3-1) and the European Standard 13816 (CEN, 2002)).

2.1.2 BRT dimensions

The above BRT definition indicates that bus rapid transit systems differ from conventional bus systems in various ways. The delineation between the two may not always be clear cut, but there are certain features that are specific to bus rapid transit systems and that may justify the listing of a system under the BRT label. Characteristic features that are observable in many existing BRT systems have been listed by Wright et al. (2007, p. 11f.) and are presented in Table 1. Departing from these common characteristics, this work identifies five principal BRT dimensions: running ways, stations, vehicles, fare collection, intelligent transport systems (ITS), service and operations plans, and branding elements. These dimensions are similar to the listing in Levinson et al. (2003, p. 13). For a bus system to qualify as a BRT system, these dimensions must be enhanced to quality levels well beyond those of conventional bus services. However, the extent of the quality improvements depends largely on local circumstances and cost constraints (Wright et al., 2007, p. 13).

Table 1 BRT characteristics and dimensions

BRT characteristics by Wright et al. (2007, p. 11f.)	BRT dimensions in this work
Exclusive right-of-way lanes	Running ways
Convenient, secure and weather-protected stations Easy access to and from other means of transport and the urban environment for all groups of users	Stations
Rapid and comfortable boarding and alighting High comfort vehicles Low-emission vehicle technologies	Vehicles
Pre-board fare collection and verification	Fare collection
Centralised system management and control Signal priority Modern information facilities	Intelligent transport systems (ITS)
Frequent and rapid service	Service and operations plan
A distinctive marketing identity Independent quality control system Excellent customer service	Branding elements

2.1.3 Organisational and institutional elements

BRT is not only a technical concept, but its implementation has to be seen in a context of organisational and institutional elements. Well organised and integrated planning that considers local circumstances is a key requirement for a successful implementation and operation of this mode. (Wright et al., 2007, p. 13) state that political will is perhaps the most important factor in the implementation of BRT systems. According to these authors, a successful BRT system invokes a feeling of confidence to its users, creates a sense of community pride, and helps to transform the very nature of a city's urban form. Moreover, the creation of favourable conditions for BRT operation is facilitated by embedding the new public transport system in a package of general improvements and transformations of the urban environment. To use an example, a main ingredient in the success story of the TransMilenio BRT system in Bogotá was the implementation of complementary measures to support public transport use. Under the leadership of a visionary mayor, Enrique Peñalosa, the city implemented 300 kilometres of new cycleways, pedestrian and public space upgrades, a Sunday closing of 120 kilometres of roadway to private motorised vehicles, and the world's largest car-free weekday. Parking and peak-hour vehicle use restrictions additionally supported the application of the Trans-

Milenio scheme (section based on Wright et al., 2007, p. 24-25). Grava (2003, p. 392) mentions that also the city of Curitiba has earned its standing as “the Mecca and Lourdes for transportation planners” not only because of its innovative and highly successful public transport system, but also due to the promotion of an effective city structure and land use distribution. Good practices in urban planning and land use development, together with an appropriate tuning of the public transport system, are key elements for the success of the intervention. In fact, the Curitiba master plan did not only imply a radical change in the public transport system, but also in upgrading the pedestrian environment and the land use management in the city. Probably, the success of the BRT systems in Curitiba and Bogotá has only been possible because of the high levels of political commitment a charismatic political leadership in promoting public transport measures (Wright et al., 2007, p. 14). Hidalgo et al. (2010a) identify a number of organisational factors that need to be considered for a successful implementation at the institutional, planning, and decision-making level:

- Involving the community through adequate information and various participation and engagement programs
- Restructuring or transforming existing bus operation and involving the existing operators through a direct negotiation of terms and conditions
- Adequate planning with sufficient funding, i.e. using experienced planning teams and capable consultants
- Top-down planning processes based on adequate governance and regulatory structures. If necessary, the public transportation authority has to be transferred to a different level of government, or new institutions have to be created
- New funding mechanisms, such as taxes and the use of extraordinary budget surplus, as well as intergovernmental grants
- Public private partnerships, where the private operators provide the equipment and services and the public sector builds and maintains the infrastructure
- Sequential implementation with clear integration of bus and other public transport services is preferable to developing isolated corridors

2.1.4 BRT as an urban multi-purpose tool: form follows function

Recent developments show that the BRT concept proves feasible and adequate in a variety of urban contexts. The ability of the BRT mode to produce a whole spectrum of transport system solutions allows for flexible and case-specific application. In some cities, such as in Curitiba, the BRT system is used to form the backbone of the public transport system. This niche is in other cities occupied by rail-based metro systems. Thus, the concepts and characteristics of a BRT system with this function will be similar to a metro system. In other cases, the urban transport system is composed of various modes occupying different functions. For example, if a city implements a BRT system to serve as a feeder service to an existing metro system or to serve corridors of minor importance, its characteristics will be closer to conventional bus operation. Chapter 3 will show that this differentiation in functions and characteristics of BRT systems can be observed in practice, and that different functions in an urban transport system require specific performance and quality characteristics of the BRT system. In short, the form of a BRT system follows its function.

2.2 Origins and evolution of bus rapid transit

In the last decades, BRT systems have become increasingly popular and are now operating in a range of cities throughout the world. This chapter will provide an overview of the origins and evolution of the BRT mode and current developments will be presented.

2.2.1 Ancestors and pioneers

The first petrol-driven motorbuses appeared in 1905 in London and Paris (Grava, 2003, p. 306). A good 30 years later, in 1937, Chicago was the first city to plan exclusive bus corridors. However, the actual implementation of bus priority measures did not occur until the 1960s when bus lanes were introduced in New York (1963) and Paris (1964). The first high-speed busway opened in 1969 on the Shirley Highway in Northern Virginia (USA) (section based on Wright et al., 2007, p. 22). The first full-scale busway concept serving an entire community was constructed in the British new town development of Runcorn in 1964, where a completely segregated busway with a length of 19 kilometres connected the centres of neighbourhoods with the town centre (Grava, 2003, p. 390). However, the development of busway concepts was not limited to industrialised countries. In 1972, the Via Expresa in Lima (Peru) was the first example of a dedicated busway facility in a developing nation. In 1977, the first busway in Africa was opened in Abidjan (Ivory Coast) (Wright et al., 2007, p. 22-23). Interestingly, the Via Expresa busway in Lima has been replaced in 2010 by a full-scale BRT system. In the 1970s, population growth, the scarcity of financial resources in public administrations, the unsatisfactory conditions in many public transport systems, and the oil crisis were main circumstances that led to the emergence of the BRT concept. In the city of Curitiba (Brazil), these conditions, together with an extraordinary commitment by city authorities and the responsible mayor Jaime Lerner, led to the creation of a low-cost yet high-quality bus concept as an alternative to an originally planned rail-based metro system. The implementation of the first 20 kilometres of the Rede Integrada de Transporte (RIT) system in Curitiba in 1974 marked the emergence of the first modern BRT system as a new transport mode (section based on Wright et al., 2007, p. 22-23).

2.2.2 Making buses rapid: the evolution of BRT elements

However, the Curitiba system was not invented from scratch. On the contrary, it incorporated the key characteristic of an exclusive right of way from preceding busway schemes and combined this approach with elements from railway systems, such as the use of high capacity vehicles and elevated stations providing level access to vehicles.

BRT evolution in Latin America

The success story of the Curitiba system was closely followed in Latin America since many cities on the continent at that time were facing rapid population growth and scarce financial resources. The oil crisis put additional pressure on many governments to find quick ways to improve public transport. The cities of São Paulo, Goiânia, Porto Alegre and Belo Horizonte followed the Curitiba example between 1975 and 1981 by constructing similar BRT systems (section based on Wright et al., 2007, p. 22-23). The initial RIT system in Curitiba was refined further by integrating inter-district services as feeder routes to the new exclusive trunk corridors, by building convenient and comfortable stations and transfer facilities, and by introducing off-board payment and a single-fare structure. However, increasing ridership started to overwhelm the system in the mid-1980s and further developments became necessary. To cope with the demand approaching 10,000 passengers per hour per direction, the system was extended by adding express routes on parallel lanes. The technological innovation of bi-articulated buses with a capacity of 270 passengers brought further improvements in capacity and the city kept its innovative reputation (section based on Grava, 2003, p. 392).

European answers

European transport planners followed the developments in Latin America with great attention, and especially in France, growing interest in busway concepts was registered. A technological innovation in the bus mode was the advent of the “O-Bahn”, the first guided busway system, in Essen (Germany). As an alternative to a planned light rail system, this city engineered a bus system where small horizontal wheels were attached at the side of the front wheels of the vehicles to control lateral motion on specially designed guideways. This innovation allowed for bus operation in a narrow tram tunnel, since the guideway significantly reduces the street space that is required for bus operation while allowing for a high speed. The concept of mechanical guidance has only been repeated by few cities, amongst others in Adelaide (Australia), Leeds (UK) and Nagoya (Japan). The relatively high costs of guideway infrastructure impeded further adoption of this concept, despite of comfort, speed, space-consumption, and image advantages (section based on Wright et al., 2007, p. 23-24). In addition, the specially shaped guideways are self-enforcing in terms of the right of way since they do not physically allow any alien vehicles to travel on them. Hence, this technology allows for a greater level of segregation from other traffic. Despite of their similarity to such approaches, rubber-tired fixed guideway systems such as people-movers at airports etc. are not part of the BRT mode, given their specialised nature. Another modification of conventional bus operation is the use of trolleybus systems. These systems offer advantages in environmental impact, smoothness of motion (i.e. comfort), durability, maintenance, and public image (Grava, 2003, p. 429). In the 1990s, new initiatives originated mainly in France to improve the quality of rubber-tired transport systems even further. Optical guidance technology and rubber-tired trams that are guided by a central rail (the translohr and TVR systems) increasingly blur the border between BRT and light rail transit (LRT) (Wright et al., 2007, p. 24). However, the use of electrical propulsion is not limited to industrial countries and a prominent example of a full-scale BRT system using trolleybus technology can be found in Quito (Ecuador).

Figure 1 Irisbus Civis: an optically guided trolleybus system in Castellón (Spain)

Source: Rabuel (2009, p. 18).

The awakening in the rest of the world

Real interest in BRT systems in Asia and North America was sparked rather late in the 1990s. Kunming was the first city in Asia to develop a busway system in 1999. New systems opened in Vancouver (Canada, 1996), in Miami (USA, 1997), and in Brisbane (Australia, 2000) (Wright et al., 2007, p. 24). The first BRT system on the African continent opened in 2008 in Lagos (Nigeria). Brader et al. (2010) conclude that public reception of the Lagos system was immediate and positive and a subsequent assessment found the scheme to be an unprecedented success.

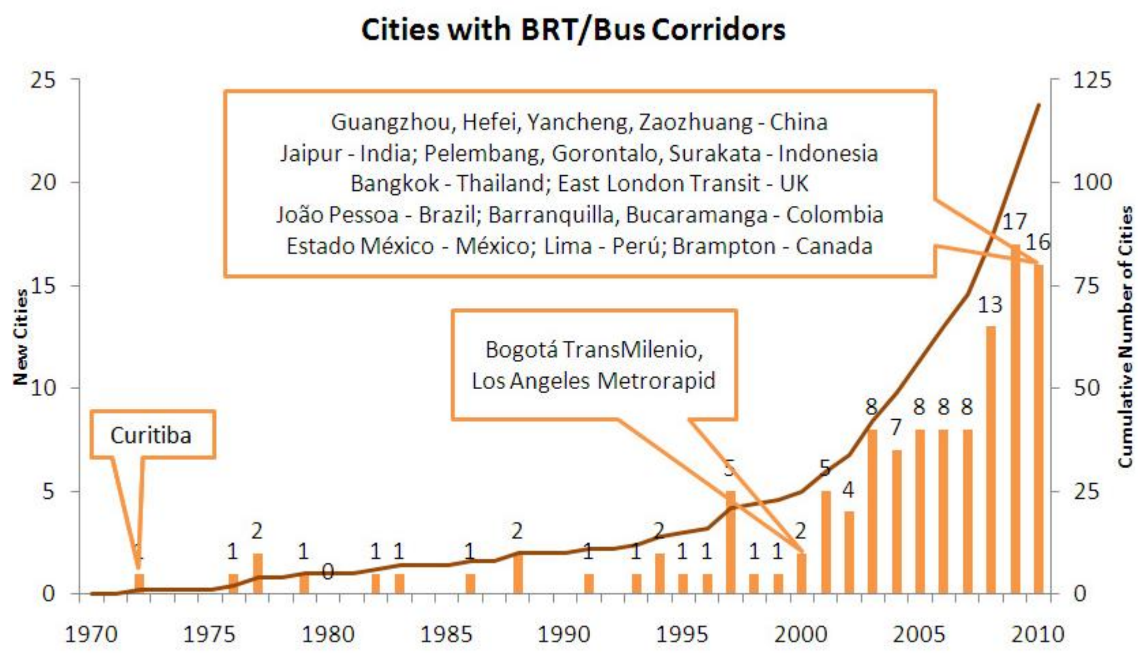
2.2.3 Formalisation of the BRT concept

Until the 1990s, the innovations in the bus sector resulted from a process of continued improvements and exchange of experiences between cities, but they were not yet regarded as the advent of a new transport mode. However, the growing number and the striking success of such initiatives raised interest in circles of transport planners, official bodies, and the producing industry. All this led to the formalisation of the BRT concept in the 1990s. As mentioned above, there is no clear definition of what is required for a bus system to qualify as a BRT system and there is no control instance deciding whether a system can be labelled BRT or not. Grava (2003, p. 393) even considers the emergence of the term of "BRT systems" as a mere labelling initiative helping to legitimise and popularise these initiatives in the broad public. However, the formalisation of the BRT concept led to official and semi-official initiatives, such as the BRT demonstration program of the US Federal Transit Administration starting in 1999, the US National Bus Rapid Transit Institute (http://www.nbrti.org) with a bus rapid transit database and the Bus Rapid Transit Policy Center (www.gobrt.org).

2.2.4 Recent developments

Figure 2 shows the dramatic increase in the number of BRT systems over the last years. By the year of 2010, more than 120 BRT systems were operating on six continents.

Figure 2 The increasing number of BRT systems in recent years



Source: Hidalgo et al. (2010b)

Key figures of the situation of BRT systems by the year 2010 are listed by Hidalgo et al. (2010b):

- 120 cities have implemented BRT Systems with exclusive bus corridors
- 26.8 million passengers are transported per weekday
- 16 cities started operations in 2010. This is a 13% growth and encompassed 21 corridors of 396 km length, 464 stations, and 2047 buses
- 49 cities currently have BRT corridors under construction
- 16 cities are expanding their corridors
- 31 new cities are in planning stages of new BRT systems.

The exploding number of systems led to the situation that in 2007, more BRT systems were under development than in existence (Wright et al., 2007, p. 15).

2.3 Chapter review

In this chapter, BRT has been identified as a transport mode that is distinguished from conventional bus systems by its higher quality and capacity, its cost-effectiveness, and its positive image. The concept encompasses a combination of high-quality vehicles, infrastructures, service and operation plans, branding elements, as well as operations management, vehicle prioritisation, and fare collection technologies. The popularity and the rapid growth of the BRT mode demonstrate that the approach has proved feasible in a variety of different urban contexts. BRT implementation requires well-organized and integrated planning and a successful BRT system helps to transform the very nature of a city's urban form. Political leadership, the involvement by city authorities, and good practices in urban planning are key elements for the success of BRT systems. With regard to the history of the BRT mode, the implementation of the RIT system in Curitiba in 1974 marked the emergence of the first modern BRT system that incorporated various elements from preceding busway schemes. Mechanically guided bus systems were developed in the 1980s. This technology offers comfort, speed, space-consumption, and image advantages, but due to the relatively high costs of guideway infrastructure, the concept has only been repeated by few cities. In the 1990s, new initiatives of optical guidance technology and rubber-tired trams originated mainly in France. Kunming was the first city in Asia to develop a busway system in 1999, and the first BRT system on the African continent opened in 2008 in Lagos (Nigeria). By the year of 2010, more than 120 BRT systems were operating on six continents, 49 cities were constructing BRT corridors, and 31 cities were in planning stages of new BRT systems.

3 Organising the BRT spectrum: system parameters and classification

The cities that have implemented bus rapid transit (BRT) systems in recent years and decades vary greatly in size, structure, density, demography, topography, and financial capability. Paralleling the diversity in cities, the public transport systems in each case face different challenges. In some cities, the BRT systems transport a large number of passengers and reach their capacity limits. In other cases, large parts of the population rely on private transport, which results in low public transport patronage and an excessive crowding of the city's road infrastructure. Accordingly, the objectives of cities towards their BRT systems are diverse. Frequent objectives are the provision of a maximum capacity to cope with a massive afflux of passengers, or a better quality of service to attract more people to use public instead of private transport. The heterogeneity of BRT cities and their individual objectives regarding the transport system is reflected in a great diversity of operating bus systems. Some cities focused mainly on introducing new and more comfortable vehicles, while others constructed exclusive running ways to accelerate conventional buses, or focused on using large vehicles and stations that allow for a higher capacity. In some cities, BRT systems serve only short corridors and transport a relatively small number of passengers, e.g. in Lyon (France), while other systems accommodate several million passengers per day, such as in São Paulo (Brazil). In short, it is not possible to define an optimal system configuration to fit all needs. The almost infinite possibilities to combine BRT elements complicate the issue of gaining an overview of theoretically possible and practically implemented system configurations.

Chapter outline: in this chapter, a new approach to organise the BRT spectrum and to classify existing system configurations will be presented and currently operating BRT systems will be analysed for their system configuration. The new classification approach is based on the BRT dimensions from chapter 2.1.2. The approach uses statistical cluster analysis for an objective and unbiased classification. Thereby, four distinct BRT classes will be identified within the variety of available system configurations. The results will be interpreted by means of graphic radar charts and rail-based systems corresponding to BRT classes will be presented.

3.1 Segregation matters: BRT and BHLS

The BRT planning guide by Wright et al. (2007) contains a classification of bus systems, which distinguishes between informal services, conventional bus services, basic busways, enhanced bus services (sometimes labelled BRT lite), BRT and full BRT. According to these authors, a bus system lacking segregated busways is not considered a BRT, even though it possesses most or all of the other characteristics of a full BRT system. These systems are labelled enhanced bus services (or BRT lite) by Wright et al. and examples are mainly found in

Europe and North America. The idea of enhanced bus services corresponds to the European approach of buses with a high level of service (BHLS), which has been developed mainly in France. For further reading on BHLS, see Rabuel (2009). Wright et al. (2007, p. 20) highlight that enhanced bus services (or BHLS systems) have achieved marked improvements in travel times, quality and patronage. However, they argue that especially in the case of North American BHLS systems a common problem has been that the improvements have relied merely upon expensive vehicle technology to create a new system image. But new vehicles alone are not a sufficient measure to meet the goals of service improvements and new ridership generation if public transport priority is not addressed due to a lack of political commitment. Since BHLS systems are also included into the BRT category by most authors, these systems will also be included in the classification approach in the next chapter.

3.2 Configuration matters: BRT cluster analysis

The previously discussed classification approach distinguished BRT from BHLS systems only with regard to the segregation level of running ways. A classification approach that takes into account more of the previously defined BRT dimensions is presented here. For this purpose, a classification framework has been developed to assess empirical data from system examples. For example, two systems with the same running way segregation characteristics but with different fare collection procedures and different branding strategies are likely to be categorized into two separate classes with this cluster analysis approach, whereas they both may figure as standard BRT systems in the previously discussed running way-based classification.

3.2.1 The classification framework

Table 2 presents a framework to classify BRT systems according to the dimensions from chapter 2.1.2. A number of sub-dimensions are used to specify the terms of running ways, stations, vehicles, fare collection, intelligent transport systems, service and operations plan, and branding elements. For the purpose of categorization, differentiating scales are introduced for all sub-dimensions. By means of these scales, BRT systems are evaluated by means of scores regarding the different dimensions. However, the scope of this classification approach is limited to a merely descriptive system comparison with regard to different system configurations. It has to be stated clearly that the approach does not provide an evaluation in terms of better and worse or a ranking of the system examples. Still, most dimensions provide some information about the degree of distinction of an analysed BRT system from conventional bus systems. In general, higher scores indicate higher levels of distinction from conventional bus systems, since the latter by definition tend to show low values regarding the classification scales in Table 2.

Table 2 A classification framework for BRT

Dimension	Sub-dimension	Score 1	2	3	4	5
Running ways	Segregation	Shared lanes in mixed traffic	Some preferential treatment: bus lanes, signs, pavement markings etc.	Designated high occupancy vehicle (HOV) lanes or queue jumper segments	Physically segregated lanes (e.g. raised markers) or at-grade busway	Exclusive alignment with full grade separation or separate busway infrastructure
	Lateral guidance	None	-	Low-tech guidance mechanism[1]	-	Mechanical or optical
Stations	Station type	Mainly basic stops with simple or no shelters	-	Mainly enhanced shelters with some identity features (corporate design) and certain passenger amenities[2]	-	Mainly enclosed stations[3] with identity features and various passenger amenities
	Platform & kerb design	Standard kerb height, mostly single-vehicle-length platform, no vehicle passing capability	-	Raised kerb to allow near-level boarding	-	Level kerb, mostly extended platforms with vehicle passing capability

[1] For example plastic strips along the platform edge to prevent vehicle damage if the drivers pull in too close.

[2] Passenger amenities include route information, message signs, displays of real-time information, newspaper boxes, drink and food vending machines, trash containers, weather protection, heating, cooling, public telephones, public art, station lighting, public address systems, emergency telephones, alarms, video camera monitoring, enhanced pedestrian linkages to urban environment, bicycle parking facilities, park-and-ride facilities, etc.

[3] Fully enclosed and weather-protected BRT stations (such as in the Curitiba, Bogotá and Quito examples), or station buildings and intermodal terminals.

Vehicles	Vehicle configuration	Out-dated standard or paratransit vehicles	Conventional standard or articulated vehicles	Enhanced[4] standard or articulated vehicles	Stylized (modern) standard or articulated vehicles[5]	Specialised (BRT) vehicles[6]
	Propulsion	Conventional internal combustion engine (mostly diesel)	Internal combustion engine with improved fuel[7]	Catenary electric drives (trolleybus), dual mode diesel & electric traction	Hybrid-electric drives	Fuel cells
Fare collection	Fare collection process	On-board	-	-	-	Off-board barrier or proof-of-payment
	Payment options	Manual cash-only	Ticket-issuing machine with cash (and/or credit/debit card)	Magnetic stripe fare cards	Transport agency-issued contactless smart cards	Contactless payment through commercial credit/debit cards and/or through mobile personal communication devices
	Fare structure	Flat fares	-	-	-	Differentiated fares
Intelligent transport system (ITS)	Vehicle prioritisation	None	-	Passive signal timing/phasing optimisation or limited active signal priority	-	Active transit signal priority and/or passive priority regulation (such as tram's general preferential right-of-way)

[4] Vehicles with enhanced passenger circulation (additional doors, enhanced standing area etc.) and/or enhanced interior amenities (lighting, windows, materials etc.).

[5] Similar to enhanced conventional vehicles, with the added appeal of stylized exterior and interior design. Sleeker, more comfortable and more easily identified and brandable, differentiating them from regular service vehicles. Step-low floors, at least three doors and quick-deploy ramps to facilitate boarding.

[6] Specially designed for operation on BRT infrastructure (e.g. platform-level floor, aerodynamic body, rail-like look, special axles, mostly with advanced propulsion systems, integrated ITS components, guidance systems and optionally with driver assistant and automation technology).

[7] Ultra low sulphur diesel, euro III diesel, compressed or liquefied natural gas etc.

	Operations management technology	None	-	-	-	Various technologies in place[8]
Service and operations plan	Route structure	Single route without service diversification	-	Overlapping routes in a corridor with skip stop or express variations	-	Integrated or network system with diverse services (locals, expresses, feeders etc.)
	Service span	Peak-period-only	-	-	-	All day
	Frequency of service	Low peak frequency (> 10 min peak headway), schedule-based	-	Medium peak frequency (5 to 10 min)	-	High peak frequency (< 5 min), headway-based
	Average station spacing	Short station spacing (< 500 m)	-	Medium station spacing (500 to 700 m)	-	Long station spacing (> 700 m)
Branding elements	Marketing classification of BRT	Minimal or no differentiation from marketing of other routes	-	Marketed as a special rapid transit route within an existing transport system	-	Marketed as a separate tier of service with special branding devices (name, logos, colours etc.)

Sources: (Diaz et al., 2009) and (Wright et al., 2007), modified.

[8] Automatic dispatch, vehicle location and scheduling software, automated passenger counters, vehicle component monitoring, passenger information and security systems etc., mostly connected to an operations centre.

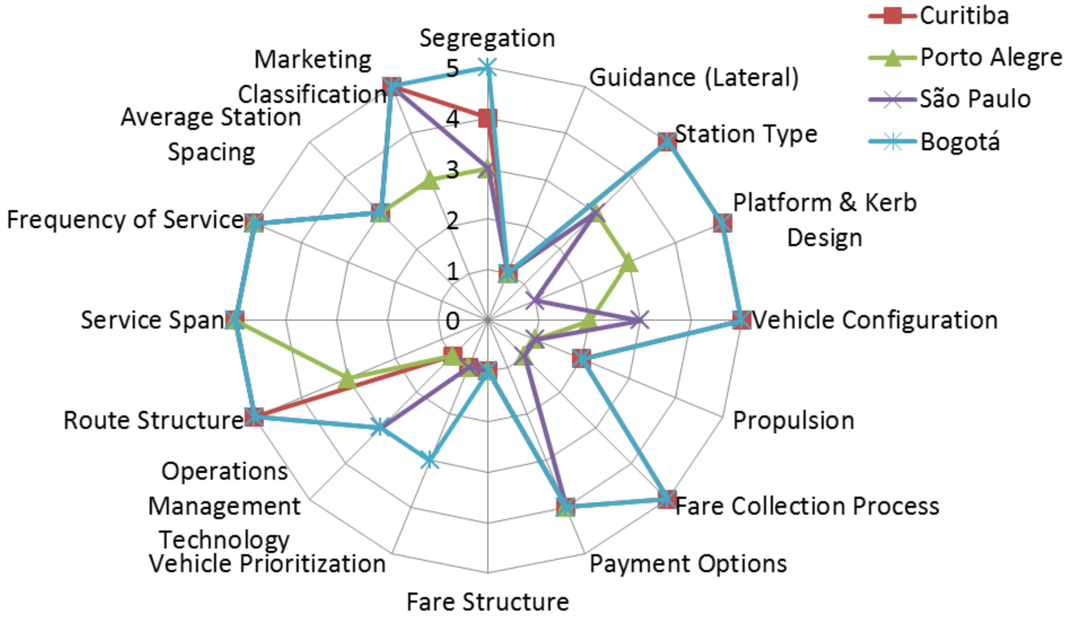
3.2.2 System examples and their configurations

The above classification framework is used in this chapter to assess data from 39 BRT system examples. The analysed system examples will be listed in Table 4 later in this work. To amplify the analysis and to provide a first insight into the characteristics of alternative transport modes, three non-BRT examples are also included: the lines 31 (trolleybus) and 2 (tram) in Zürich (Switzerland), and a low-tech suburban rail service in San José (Costa Rica). The selection used quantitative and qualitative data by Diaz et al. (2009), Wright et al. (2007), Rachdi (2011), Weidmann et al. (2011) and NBRTI (2011). Unfortunately, the data are very heterogeneous and of a mixed quality, showing a large number of missing values and some obvious inconsistencies. The scope of this work only allowed for a rough data review to eliminate the most obvious inconsistencies and errors. A thorough data review and the collection of missing values would help to improve the quality of data and allow for a more precise classification and evaluation of systems.

A first graphical system comparison

In a first run of the classification approach, the systems were analysed for all sub-dimensions from chapter 2.1.2. As an example, a graphical representation of the scores of four well-known Latin American BRT systems is displayed in Figure 3. The figure shows that the systems of Curitiba (Brazil) and Bogotá (Colombia) perform similarly in many dimensions, whereas the systems of Porto Alegre and São Paulo (Brazil) often show a different pattern.

Figure 3 Colombian and Brazilian BRT systems compared



The meaning of the individual scores (1-5) regarding the different BRT sub-dimensions can be looked up in Table 2. For example, a score of 3 for the sub-dimension of segregation indicates designated HOV (high-occupancy-vehicles) lanes and queue jumper segments, which is the case in Porto Alegre and São Paulo. The scores in this sub-dimension indicate that Curitiba uses segregated facilities and at-grade busways, whereas in Bogotá, the system features exclusive alignment, full grade separation, and separate busway infrastructure. The score of 1 in the lateral guidance sub-dimension indicates that none of the analysed systems uses lateral guidance technology. The fare collection process is off-board in Curitiba and Bogotá and on-board in Porto Alegre and São Paulo. All systems use transport agency-issued smartcards as an advanced payment option and have a flat fare structure. Vehicle prioritisation is only used in the Bogotá system and only Bogotá and São Paulo use operations management technology. The systems are quite similar in terms of service and operations plans and the average station spacing is between 500 and 700 metres in all systems. Interestingly, the level of segregation is mirrored in the dimensions station type, platform & kerb design, and vehicle configuration. The Curitiba and Bogotá systems show the highest scores in all of these sub-dimensions. Hence, this first graphical analysis provides an indication that there might be an underlying pattern in system configuration, and that it might be possible to identify system examples with similar characteristics.

Dimension reduction

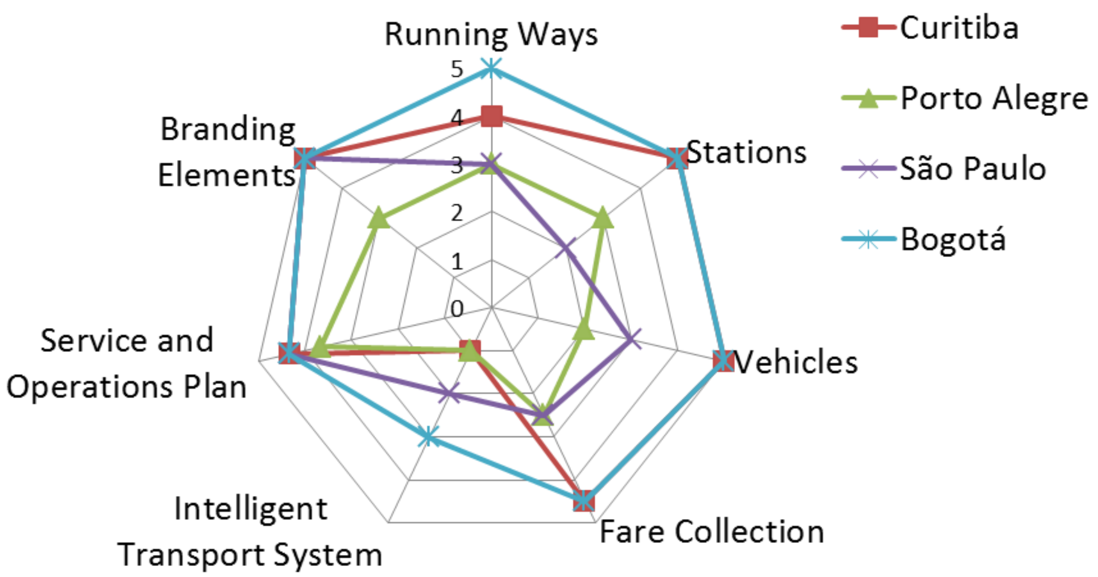
The above evaluation of four selected system examples showed that the inclusion of all sub-dimensions conveys a very detailed analysis. However, the high level of detail is traded off against a clearer picture that could be gained when considering fewer dimensions. Therefore, the 16 sub-dimensions will be reduced in a next step to the seven main BRT dimensions from chapter 2.1.2. To calculate a score for each BRT dimension out of the individual scores in the sub-dimensions, care had to be exerted to avoid meaningless values. For example, it would not be reasonable to combine the segregation and lateral guidance sub-dimensions to calculate an average score for the running ways dimension. The two sub-dimensions express completely different things and the latter is a purely binary description of whether or not a system uses lateral guidance technology. Therefore, calculation rules were defined to generate dimension scores out of sub-dimension scores. These are summarised in Table 3. Even more than in the case of the sub-dimensions, it has to be highlighted that the scores in the BRT dimensions do not provide a quantitative assessment or statements about system quality. They should be interpreted merely as a help for classification and as crude indicators for the difference of a system to a conventional basic bus system. In general, it can be said that with higher scores on all dimensions, the difference to conventional bus systems increases, since conventional bus systems tend to show low values (mostly 1) in all BRT dimensions.

Table 3 Calculation rules for BRT dimension scores

BRT dimension	Calculation rule
Running ways	*Segregation* score only; *lateral guidance* was excluded from analysis
Stations	Average score of *station type* and *platform & kerb design*
Vehicles	*Vehicle configuration* only; *propulsion* was excluded from analysis
Fare collection	Average score of *fare collection process* and *payment options; fare structure* was excluded from analysis
ITS	Average score of *vehicle prioritisation* and *operations management technology*
Service and operations plan	Average score of *route structure, frequency of service* and *average station spacing; service span* was excluded from analysis
Branding elements	*Marketing classification* only

To use the above examples, the systems of Curitiba, Porto Alegre, São Paulo and Bogotá are compared again in Figure 4. This time, only the scores in the seven main BRT dimensions are displayed.

Figure 4 Main dimensions of selected Colombian and Brazilian BRT systems



In general, the systems of Curitiba and Bogotá show at least equal, but in most dimensions substantially higher scores than the Porto Alegre and São Paulo examples, except for the absence of intelligent transport systems in the Curitiba example. This observation supports the findings of Wright et al. (2007, p. 14) that the systems of Curitiba and Bogotá are to be considered full BRT systems, since they encompass close to all relevant BRT features. In contrast, systems with the characteristics of Porto Alegre and São Paulo are closer to conventional bus operation. Systems with these characteristics are hence often called standard BRT or BRT light (or BRT lite). This analysis shows that the two full BRT systems do not only show a higher level of segregation from other traffic; they also have higher scores in most of the other BRT dimensions. This indicates already that there might be an underlying pattern.

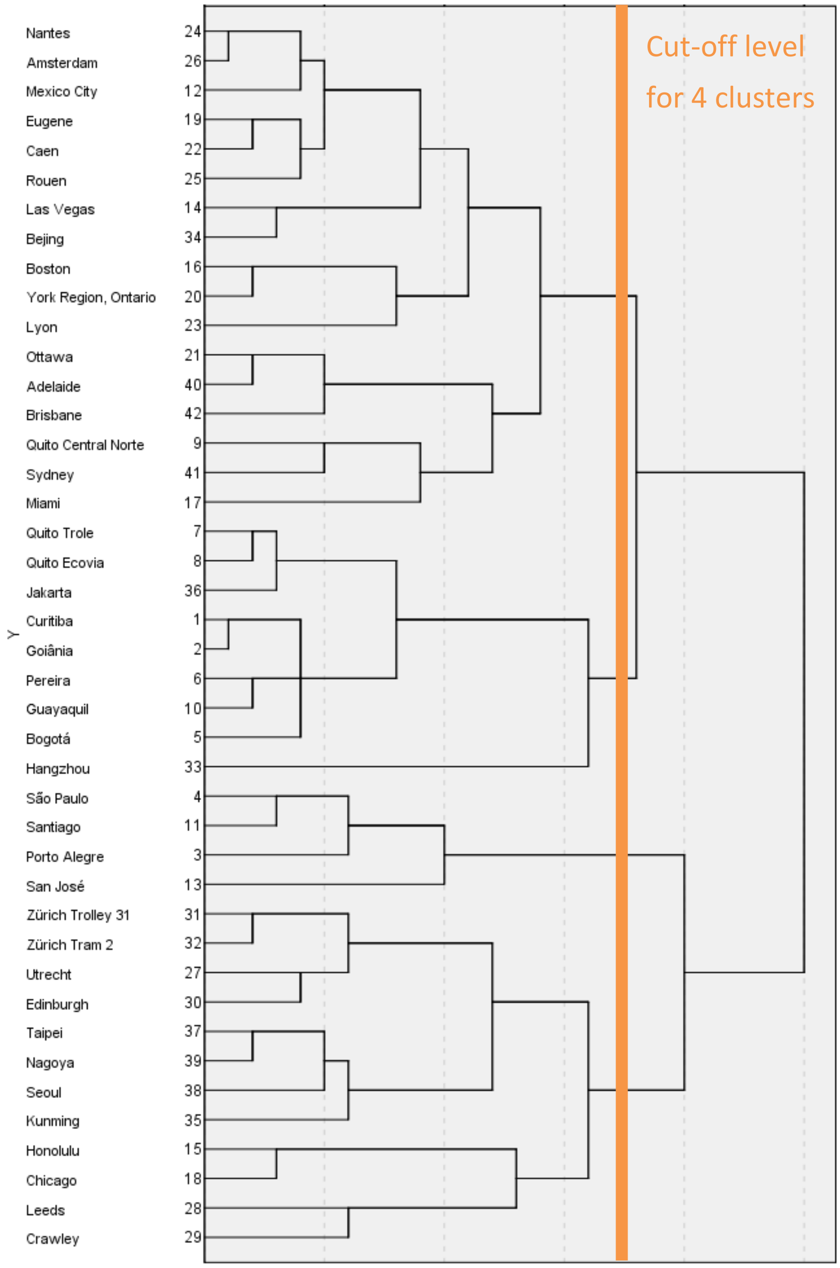
3.3 BRT classes

The method of graphically comparing scores in different BRT dimensions to identify typical system configurations will be extended in this chapter. An approach that uses statistical cluster analysis to classify existing BRT system examples will be presented and applied. The goal of this approach is to use an objective statistical method to identify common characteristics in existing systems that allow the identification of separated groups and facilitate an objective classification. The sample of 42 operating systems (39 BRT plus 3 non-BRT systems) will be divided into four classes regarding similarities and differences between the systems in all of the seven previously mentioned BRT dimensions.

3.3.1 Cluster analysis

In this section, the statistics software package SPSS is used to perform a hierarchical cluster centre analysis to classify all sample systems. The target number of clusters was pre-set to 4, to allow for the identification of sufficiently distinct classes. If the number of clusters was set to be higher, the clusters would become too similar and the identification of differences between classes would become difficult. In the cases of Santiago (Chile), Eugene (USA), Lyon and Nantes (France), and Leeds (UK), not all dimension scores could be extracted because of missing data entries and they had to be estimated and completed manually. With the complete set of scores, different clustering methods were applied and tested for congruent results. With the method *linkage between groups,* the program converged in the 7^{th} iteration and delivered the result displayed in Figure 5. The clustering method first detects the examples with the greatest similarities in scores and joins them into a so-called cluster. This process continues by joining more and more examples in a stepwise manner. The digit to the right of the city name in Figure 5 indicates the step in which the program joined the examples into one group. In this case, the systems of Curitiba and Goiânia have the greatest degree of similarity and were joined first. The tree-shaped structure of the results originates from the stepwise joining of the most similar examples, and the joins are indicated by connecting lines. After finishing the clustering process, the “tree” can be cut by a vertical line at any point to identify clusters. Moving the cut-off line from the right side of the figure to the left leads to an increased number of clusters each time a “branch division” is passed. The red line in Figure 5 indicates the cut-off at the level of four clusters. Each "branch" of the tree that points to the left side contains the examples within one cluster.

Figure 5 Hierarchical cluster analysis with the method *linkage between groups*

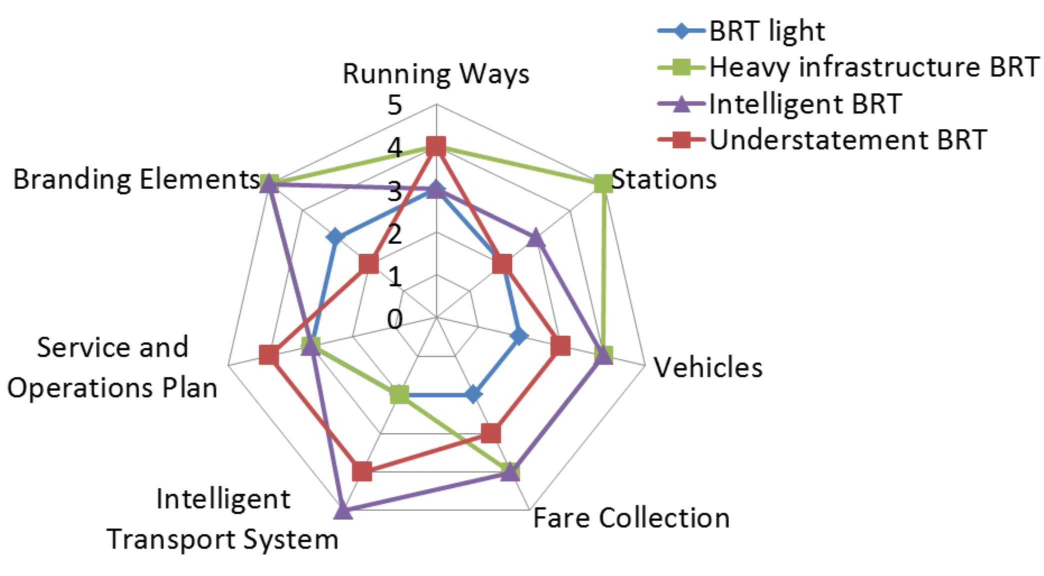


It has to be highlighted that the identification of clusters largely depends on two factors. On one hand, the clustering method has a considerable influence on the identification of clusters. Annex A 2 contains a comparison of results between the above clustering method *linkage between groups* and the method *furthest neighbour*. On the other hand, the selection of examples itself determines the characteristics of the identified clusters. For instance, if all the examples within the uppermost branch between the cases of Nantes and Miami were excluded from the analysis, the remaining examples in the clusters would lead to completely different cluster compositions and cluster centres. Hence, a certain degree of caution should be exerted in the interpretation of the resulting clusters, since the selection of system examples in this work was principally led by the availability of data and not by the requirement of obtaining a representative sample of all existing BRT systems. The inclusion of three non-BRT systems does not seem to distort the picture, since the San José rail system shows a system configuration similar to the systems of São Paulo, Santiago, and Porto Alegre. The Zürich trolleybus and tram lines have configurations similar to the BRT systems of Edinburgh and Utrecht.

3.3.2 Identifying BRT classes

The four clusters that have been identified above are now analysed for their average scores in the different dimensions to provide an insight into common characteristics within each of these four BRT classes. In each cluster, an average score in each dimension has been computed by taking the respective average dimension scores of all examples within the cluster. These cluster average scores can then be plotted in radar charts, as it was done in the case of the Brazilian and Colombian examples in Figure 4. An analogue representation for the cluster averages is displayed in Figure 6.

Figure 6 Average dimension scores of BRT classes



Heavy and light BRT

The cluster average that is represented by a green line shows high scores in running ways, stations, vehicles, fare collection, and branding elements, but low scores in ITS and service and operations plan. Hence, the systems with these characteristics are mainly corridor-based BRT systems with quite short station spacing and a limited use of intelligent transport system technologies, such as vehicle prioritisation and operations management tools. Fare collection is performed off-board and modern and varied payment options such as agency-issued smartcards are widely in use in these systems. The systems within the green cluster distinguish themselves from conventional bus systems principally by the use of exclusive running ways, specialised vehicles, and enclosed stations. They are mostly branded and marketed as a specialised tier of service, apart from conventional buses. Because of these characteristics, this group is labelled *heavy infrastructure BRT* (or *BRT heavy / heavy BRT*, in short). A second cluster, depicted by a blue line, has relatively low scores in all dimensions. Because of its limited differentiation from conventional bus systems, this class is labelled *BRT light*.

Intelligent and understatement BRT

Two classes that are harder to define are represented by purple and red lines. The systems represented by a purple line show the highest possible score in the use of ITS, but lower scores in running ways, stations, and service and operations plan. Hence, the systems in this cluster are mainly corridor-based systems with a low frequency of service and relatively low average station spacing. Vehicle priority and the according advantage in higher operating speeds and reliability are achieved mainly through the use of ITS technology, and not through physical segregation of running ways. Like the class of heavy infrastructure BRT, these systems use specialised BRT vehicles and are branded as special transport modes. Because of the intense use of ITS technology, this class is labelled *intelligent BRT*. In contrast, the systems represented by a red line are normally not branded as a special tier of service and are therefore labelled *understatement BRT*. These systems largely use exclusive running ways, while featuring mainly standard stations and vehicles. Fare collection is frequently performed before on board, and payment options are offered at an intermediate level. The use of ITS technology is quite widespread in this class and the high score in service and operations plan indicates that these systems tend to form networks while having a higher frequency of service and longer station spacing. These four BRT classes will be analysed further in this work, and the respective colours from Figure 6 will be maintained in following illustrations to ease recognition.

Light does not mean small

It is important to note that the above classification is based only upon system parameters and configurations, and not upon performance, size, or cost characteristics. It should be clarified that, for example, BRT light does not mean that these systems are small in size. The São Paulo BRT is an example of a BRT light system, but it transports almost 2,800,000 passengers per day, whereas this figure is just above 500,000 in the case of the heavy infrastructure BRT system of Curitiba. Additional indicators of size and costs for the different BRT classes can be found in Table 18 in annex A 3.

The geographical pattern in BRT classes

Table 4 displays the system examples and their belonging to the different BRT classes. The system examples are listed by continents to analyse if there is a pattern in the geographical distribution of BRT classes. No examples from Africa have been included into the analysis since no data could be found, even though there are systems in operation in Lagos (Nigeria), Cape Town, Johannesburg and Port Elizabeth (South Africa).

Table 4 BRT system examples, listed by class and continent

	Heavy infrastructure BRT	BRT light	Intelligent BRT	Understatement BRT
Asia	Hangzhou, Jakarta	-	Beijing	Kunming, Taipei, Seoul, Nagoya
Europe	-	-	Caen, Lyon, Nantes, Rouen, Amsterdam	Utrecht, Leeds, Crawley, Edinburgh, Zürich (trolleybus 31 & tram 2)
Oceania	-	-	Adelaide, Sydney, Brisbane	-
North America	-	-	Las Vegas, Boston, Miami, Eugene, York Region (Ontario), Ottawa	Honolulu, Chicago
South America	Curitiba, Goiânia, Bogotá, Pereira, Quito (Trole & Ecovia), Guayaquil	Porto Alegre, São Paulo, Santiago, San José (rail system)	Quito (Central Norte), Mexico City	-

Table 4 indicates that within the analysed sample, heavy infrastructure BRT are only found in South America and Asia. All BRT light examples originate from South America and include the large systems of São Paulo (Brazil) and Santiago (Chile). Also the low-tech rail system in San José (Costa Rica) would fall into the BRT light category since its system configuration is similar to the above BRT systems. The examples that fall into the category of intelligent BRT are mainly found in Europe (France), Oceania (Australia) and North America. In the classification by Wright et al. (2007), some of these systems fall into the category of BHLS. Understatement BRT systems include systems in Asia (China, Taiwan, South Korea and Japan), as well as in Europe (UK and Switzerland) and in the USA. It is interesting to note that the non-BRT trolleybus and tram systems of Zürich (Switzerland) are found in this category. When considering the characteristics of the other systems in the understatement BRT category (especially the UK systems), the question can be raised if these systems should be labelled BRT systems at all. In the case of Leeds (UK), for example, the so-called BRT system is basically a conventional bus system with some isolated and short sections where buses can pass car queues on segregated busways. The fact that the busways and vehicles are fitted with mechanical guidance technology should not obscure the fact that the other characteristics of the Leeds system do not really argue for including it into the BRT category. Also when looking at performance characteristics rather than at system configuration, these systems prove to be almost equal to conventional bus services (see chapter 5.3.3). Wright et al. (2007, p. 20) argue that the BRT label should not be expropriated to systems that make only a marginal effort towards performance improvement. Nevertheless, understatement BRT systems are also included in the further analysis to assess their performance in comparison to the other BRT classes.

3.3.3 Summarising BRT classes and corresponding rail systems

Table 5 provides an overview of the four identified BRT classes and their characteristics. Additionally, the table compares the BRT classes to rail-based systems with similar specifications and characteristics.

3.4 Chapter review

An objective classification of real-world system examples resulted in the identification of four distinct BRT classes. Heavy infrastructure BRT systems are mainly corridor-based systems that are clearly distinguished from conventional bus systems by using segregated busways, specialised vehicles, enclosed stations, and modern off-board payment options, such as agency-issued smartcards. BRT light systems have small differences to conventional bus systems in all BRT dimensions. These systems often have short headways between services and operate in networks. Intelligent BRT systems are distinguished from conventional bus systems mainly through the use of specialised BRT vehicles, vehicle prioritisation, and operations management technology. These systems are focused on comfort and speed improvements and are mainly found in France, Australia, and North America. Often, these systems are branded as special tiers of service and have also been labelled BHLS (buses with a high level of service). Understatement BRT systems use mainly standard stations, vehicles and payment procedures. They have small or no visible differences to conventional bus systems and are normally not branded as a special tier of service. It is possible to identify rail-based systems with specifications and characteristics that are similar to the different BRT classes.

Table 5 Summary of BRT classes and corresponding rail-based systems

BRT (or bus) system, typical examples	BRT (or bus) system characteristics	Corresponding rail system, typical example, system characteristics	
Heavy infrastructure BRT  Image: Curitiba (Brazil) Examples: mainly found in South America and Asia	- *Running ways:* often completely segregated - *Stations:* fully enclosed, rapid boarding and alighting procedures - *Vehicles:* specialised, with level access, often bi-articulated buses - *Fare collection:* off-board, barriers, often modern payment options (mostly agency-issued smartcards) - *Intelligent transport systems:* low level of vehicle prioritisation and operations management technology - *Service and operations plan:* mainly corridor-based, short average station spacing, high frequency of service - *Branding elements:* branded as a special tier of service - *Focused on:* capacity improvements, less on speed and reliability	**Completely segregated LRT, heavy rail or sub-surface metro**  Zürich (Switzerland)	- Tracks often completely segregated - Enhanced or underground stations with rapid boarding and alighting - Specialised vehicles - Off-board fare collection - High level of signalling and operations management technology
Intelligent BRT  Image: Caen (France) Examples: mainly found in Europe (France), Australia and North America	- *Running ways:* often not physically segregated - *Stations:* conventional stops - *Vehicles:* specialised BRT vehicles, sometimes with guidance technology - *Fare collection:* off-board, proof-of-payment systems and modern payment options - *Intelligent transport systems:* high level of vehicle prioritisation and operations management technology - *Service and operations plan:* mostly corridor-based, varied average station spacing, low frequency of service - *Branding elements:* mostly branded as a special tier of service, sometimes labelled BHLS systems (buses with a high level of service) - *Focused on:* comfort and speed improvements, less on capacity	**Modern LRT or tram operation**  Phoenix (USA)	- Tracks mostly segregated - Standard or slightly enhanced stations - Modern stylised vehicles - Off-board fare collection - High level of signalling and operations management technology - Often intensively branded and marketed

BRT light

São Paulo (Brazil)

Examples: mainly found in South America

- *Running ways:* mostly bus lanes but no physically segregated busways
- *Stations:* standard basic stops
- *Vehicles:* standard or slightly enhanced vehicles
- *Fare collection:* mostly on-board
- *Intelligent transport systems:* low level of vehicle prioritisation and operations management technology
- *Service and operations plan:* mostly network-based, high to very high frequency of service
- *Branding elements:* often branded and marketed as a special tier of service, despite of similarity to conventional bus systems
- *Focused on:* low cost and high capacity, less on reliability and comfort

Understatement BRT

Leeds (UK)

Examples: mainly found in Europe (UK), Asia and North America

- *Running ways:* mostly segregated busways or queue jumper segments
- *Stations:* standard basic stops
- *Vehicles:* standard vehicles
- *Fare collection:* mostly on-board
- *Intelligent transport systems:* high level of vehicle prioritisation and operations management technology
- *Service and operations plan:* network structure, high frequency of service and longer station spacing
- *Branding elements:* normally not branded as a special tier of service
- *Focused on:* speed and reliability

Conventional LRT or tram operation

St. Gallen (Switzerland)

- Tracks only partly segregated
- Standard vehicles and stations
- Mostly off-board fare collection
- Basic signalling and operations management technology

Conventional bus service

Jena (Germany)

Examples: found in most cities around the world

- *Running ways:* mostly not segregated
- *Stations:* standard basic stops
- *Vehicles:* standard vehicles
- *Fare collection:* mostly on-board
- *Intelligent transport systems:* mostly none or at a low level
- *Service and operations plan:* mostly network structure, varied frequency of service, mostly short station spacing
- *Branding elements:* normally none
- *Focused on:* low cost

Non-prioritised tram operation

Zürich (Switzerland)

- Operation in mixed traffic
- Standard vehicles and stations
- Off-board or on-board fare collection
- Basic or no signalling and operations management technology

Informal public transport

Lima (Peru)

Examples: mainly found in cities in developing countries

- *Running ways:* not segregated
- *Stations:* none or standard basic stops
- *Vehicles:* out-dated or inappropriate vehicles
- *Fare collection:* manually on-board
- *Intelligent transport systems:* none
- *Service and operations plan:* mostly not clearly defined, varied frequency of service, extremely short stop spacing due to informal stopping
- *Branding elements:* none
- *Focused on:* competition, low cost, normally no quality targets

Out-dated rail services

Agra (India)

- Mixed levels of segregation
- Out-dated vehicles
- Basic or no signalling and operations management technology
- Uncomfortable, unsafe, slow, and unreliable operation

Image credits: Scruggs (2011), www.gobrt.org (2011), www.academic.ru (2011), http://dbpedia.org (2011), URL (2011b), Peter Ehrlich (in Light Rail Now Project Team, 2009), Schramm (2011), Sauter (2004), Plater (2007).

4 Perspectives on system performance

According to BRT advocates, the performance and amenity characteristics of bus rapid transit are similar to modern rail-based systems but can be obtained at much lower cost and faster implementation times (Wright et al., 2007, p. 11). This chapter aims at clarifying what is meant by “performance and amenity characteristics”. The components of system performance of urban public transport systems will be analysed in general terms and specifically for BRT systems. Vuchic (2005, p. 525) highlights the need for developing a broader understanding of the performance of public transport modes and emphasizes that the evaluation and comparison of public transport modes should not only base upon comparisons of costs.

Chapter outline: this chapter will firstly provide a general overview of actors and their needs. Secondly, the possibilities to influence performance at the stages of strategic and tactical planning and at the level of operational practices will be discussed as well as the influence of system context elements. Then, the individual perspectives of actors will be discussed in more detail. Quality, understood as the user’s perspective, will be defined and addressed specifically from a BRT perspective. The influence of different BRT elements on quality criteria will be discussed as well as the quality limitations of this mode. Capacity is understood as the operator’s perspective and will be addressed as well as cost-efficiency, understood as the community’s perspective. In particular, the influence of public transport priority and right-of-way (ROW) measures on quality and capacity will be highlighted, as well as causes for unreliability in public transport.

4.1 Actors and their needs

Vuchic (2005, p. 528) identifies three groups of actors that have interests and requirements towards urban transport systems and that are affected by their operation. The first group of actors, the passengers, are the most important party. They want to have good service at a reasonable price. The second party, the transit operator, must provide the service and meet a certain service quality level to attract passengers. At the same time, he has to maximise efficiency of operations, i.e., minimise the costs for a given service quality. The third party is the community or city. This group represents the local government and the entire population of the served area, including passengers. The last group also includes state and federal governments, which are, or should be, interested in promoting an economically and socially viable environment, quality of life, and energy conservation (section based on Vuchic, 2005, p. 528). The requirements of these three groups of actors are summarized in Table 6.

Table 6 Requirements of different actors towards transport systems

Passengers	Operator	Community
Availability	Area coverage	Service quality / passenger attraction
Frequency / headway	Reliability	System cost
Punctuality / reliability	Cycle speed	Reliability in emergencies
Speed / travel time	Capacity	Social objectives
Comfort	Flexibility	Environmental impact
Convenience	Safety and security	Energy consumption
Security and safety	Costs	Long-range impacts
User cost	Passenger attraction	
	Side effects	

Source: Vuchic (2005, p. 530)

Obviously, some of the above requirements are not compatible with each other, whereas other interests of actors coincide. Examples of two conflicting objectives are the requirement of the users to find a transport system with a high comfort standard and the requirement of the operator to run the service at low operating costs. In any case it will not be possible to meet the requirements of all interested parties completely, and trade-offs will have to be made between the different interests and requirements of actors. An example where the interests of actors coincide is a high quality level. Quality is not only important to users, but also to operators and the community in order to generate public transport ridership. White (2002, p. 59) lists the case of Leeds (UK) as an example where private bus operators are contributing heavily in quality improvements of the urban bus system by financing a new guided bus scheme. These investments are made by the operators because they will allow for a higher commercial speed of the system. Because of these speed improvements, benefits are expected from reduced operating costs by saving vehicles and from increased patronage, which implies higher revenue. Since every transport mode has its own distinct characteristics, the degree to which a transport mode satisfies the different requirements will vary greatly. For instance a subway system will meet the goal of high speeds quite well, but perform rather badly regarding the construction cost criterion. Or a heavily underused BRT system may perform well from the user's point of view because there is always enough space available, but probably not from the operator's perspective, when he is looking at the balance sheet with the financial results. Hence, a certain trait of performance can be considered positive or negative; depending on the actor who is looking at it. The following chapters will therefore aim at assessing performance from the different actors' perspectives and identify the influence of particular BRT elements on the respective performance levels.

4.2 Planning for performance

At every stage of the planning, implementation and operation process, there are possibilities to influence the performance of a transport system. This chapter will identify target dimensions and control parameters at the stages of strategic and tactical planning and at the level of operational practices. The influence of these control parameters on system performance will be analysed in general terms. Since transport systems are always embedded in a set of local conditions, such as physical-geographical characteristics of a city, the influence of system context elements on performance will also be included into the analysis.

4.2.1 Strategic and tactical planning

The early phase of strategic planning is probably the stage at which the performance level of a public transport system can be influenced most. At this stage, the choice of a transport mode is made and the network layout is specified. Thus, there are great degrees of freedom in the localisation of running way infrastructures and stops, the size and specification of vehicles, and the technology level of signalling and operations management. Other parameters, such as the schedule and the frequency of service have to be included into the strategic planning to a large extent, since they depend both on the available infrastructure capacity and on the number of vehicles and staff, which need to be planned well in advance.

Conflicting targets and target dimensions

Paralleling the previously discussed interests of actors, the strategic planning process needs to consider conflicting target dimensions. Weidmann (2008) lists conflicting targets at the stage of strategic planning. An important trade-off at this stage exists between accessibility and commercial speed. An extensive area coverage by short station spacing conflicts with the provision of fast links between areas. To resolve this conflict, Weidmann suggests to differentiate services in fast-running express routes and slower local services, as it is implemented for example in Curitiba and Bogotá. Public transport systems have to meet a disperse travel demand with a finite number of lines, services and departures. Therefore, a core objective of the planning process is a good fine tuning of the line structure, an optimal choice of connection points, and a market-oriented specification of service hours. Generic target dimensions of the strategic planning process are configuration, capacity, and conditions. Hence, the system architecture should meet demanded travel relations in an optimal way, and all system elements should provide for a sufficient capacity while assuring defined standards of user quality (section based on Weidmann, 2008, p. 5/104). For economic reasons, the capacity or quality of service of a system cannot simply be expanded to a maximum, but the different target dimensions need to be carefully weighed up against each other and case-specific priorities need to be set. Ideally, a system should meet the quality requirements of users in the most cost-efficient way to the operator and with a minimal negative impact on the community and the environment.

Control parameters in strategic planning

In strategic planning, the system components of vehicles, stations, running ways, depots, signals etc. can be specified together with their interactions in space and time. All system components need to be at the right location at the right time in the right quantity and configuration to deliver an optimal system performance (Weidmann, 2008). Table 7 lists the parameters that can be influenced at the stage of strategic and tactical planning and the performance elements that are influenced by these parameters.

Table 7 Control parameters in strategic planning

Performance element	Control parameters in strategic planning
Accessibility	Localisation of stations, service pattern, network layout
Availability	Frequency of service, service pattern at stations, maintenance concept
Frequency	Timetable, unit capacity
Commercial speed	Vehicle specifications, station spacing, running ways specification, maintenance concept, propulsion technology
Reliability	Vehicle, stations, and running ways specification and maintenance concept, line and station capacity
Comfort	Vehicle, stations, and running ways specification, maintenance and cleaning concept

Source: Weidmann (2008, p. 32/104 - 53/104)

4.2.2 Operational practices and performance

At the stage of operational planning, the actual production of the public transport service is specified. Parameters at this stage include the number of required vehicles, maintenance intervals, or the exact schedules. In operational practice, only a limited amount of changes can be made to the system. Nevertheless, changes in the operational practice are possible at short notice and can still have a large impact on system performance. For example, the extension of the service span substantially increases the availability (and thus the quality) of a transport system and can mostly be implemented by changes at the level of operational practice. Flexible disposition concepts and the provision of vehicle and staff reserves for the case of irregularities at strategic points in the network can help substantially in increasing system performance in terms of reliability, and thus quality of service.

4.2.3 System context elements and performance

Some factors influencing system performance can only partially be influenced in system planning. These external boundary conditions, or system context elements, include local economic, social, environmental, and physical-geographical conditions, as well as cultural elements. For example the limited availability of street space in a central business district might impair the implementation of transport systems that use a lot of street space, or even completely inhibit the use of surface transport systems. The influence of system context elements can be illustrated using the example of Quito (Ecuador). The situation of limited street space in the protected historical city centre is illustrated in Figure 7. Even though the system already today operates at its capacity limit, it is not possible to expand it by adding parallel running ways. For this reason, it has been proposed to upgrade this BRT to a rail-based system (Hidalgo et al., 2010a).

Figure 7 The heavy BRT system of Quito (Ecuador) operating in a narrow street space

Image source: Haseldine (2007).

The system context element of topography also influences travel time since the acceleration and braking characteristics of vehicles mostly lower commercial speed in hilly situations. Topography might even have an impact on the choice of mode and traction. Extreme topographic conditions might impair the use of rail-based systems due to limited adhesion. Electric traction and rubber tyres offer particularly significant advantages in terms of the dynamic performance in corridors with a high gradient and frequent acceleration and braking (Vuchic, 2005, p. 100). System context elements can also influence public transport patronage. For example, if the topography or the street patterns of cities lead to a substantial prolongation of the actual access ways in comparison to the crow-fly distance. Then, accessibility to the transport system is reduced because of longer pedestrian access distances, and the system potentially attracts less passengers (Kittelson & Associates Inc. et al., 2003, p. 3-38) System context elements are always of a very local nature and have to be addressed specifically for each case.

4.3 Quality – the user's perspective

Quality of service is defined in a broad sense as "the overall measured or perceived performance of transit service from the passenger's point of view" (Kittelson & Associates Inc. et al., 2003). Even though this general definition is hardly challenged, the listings of elements that are important from the passenger's point of view vary greatly between different sources. The definition also implies that performance aspects which are not directly relevant to customers, such as operating costs or capacity, are not considered as a part of the quality of service. This chapter will address quality of service form a general point of view to provide a basis for the quality evaluation of BRT systems in chapter 4.4. Firstly, the difference between delivered and perceived quality is discussed. Secondly, levels of service (LOS) are presented as a means to quantify and display quality components in a comparable way. And finally, quality of service components and indicators are listed.

4.3.1 Sought, targeted, delivered and perceived quality

The above definition of the quality of service implies that quality contains not only objectively measurable aspects, but also the user's perception and thus a certain degree of subjectivity. Accordingly, the delivered quality by the operator does not always coincide with the quality that is perceived by the user. Some quality indicators objectively measure the quality that is actually delivered to the customer, such as the number of criminal incidents per passenger kilometre as an indicator of the security in a system. However, the passenger's perception may in some cases be greatly independent of the actually delivered quality. The perceived personal security in a poorly lit, unclean, empty, and anonymous subway wagon, for example, may be perceived as very poor, even though the number of criminal incidents per passenger kilometre might in the particular case be quite low. Depending on the indicator, the security performance of the service may in this case be valued as very good or very poor. Both these objective and subjective views on quality are incorporated in the quality management circle of the European standard EN 13816 (CEN, 2002 p. 7). The quality of an urban bus service is perceived and valued by individuals. Therefore, quality must be seen in a context of the experiences, expectations, and perceptions of human beings. More concretely, users compare the performance of a new system to their experience from a previous system. For example, if a transport system is upgraded from an informal service with a very poor quality of service to something close to what is considered a conventional bus operation in industrialised countries, the quality improvement that is perceived by users can be significant, even though the actual and measurable performance still lingers at a low level. This finding helps to explain why some bus systems in practice have been labelled as BRT systems, even though the analysis in chapter 3 of this work identified them as being very similar to conventional bus systems. In short, perception plays a role when defining whether a bus system is a BRT or not.

4.3.2 Quality evaluation

Performance can be measured by indicators, which are designed to allow for a measurable and comparable evaluation. Performance indicators and indices can be applied to assess the effectiveness of transport systems, and to identify trends or problems (based on Litman, 2008). However, the choice of performance indicators and the interpretation of outcomes depend on which actor's perspective the analysis chooses to take. Kittelson & Associates Inc. et al. (2003, p. 3-4) provide an overview of performance indicators considering the perspectives of different actors. Litman (2008) stresses the importance of a careful selection of performance indicators and delivers a listing of appropriate indicators for the analysis of transport systems. Following his argument, inappropriate or incomplete indices can misdiagnose problems and misdirect decision-makers. For example, an index that only considers quantities tends to encourage the production of abundant but inferior output, while an index that only considers quality can result in high quality output but in inadequate quantities of production. This claim holds as well for the evaluation of BRT systems and implies that only a performance evaluation that considers both quality and quantity (i.e. quantitative capacity and cost figures) can unveil a complete picture of system performance. The European standard EN 13816 (CEN, 2002) in its annex C lists a number of methods for measuring public transport quality yielding quantitative and qualitative information about the performance of a transport system. However, Kittelson & Associates Inc. et al. (2003, p. 3-22) remark that these values, by themselves, provide yet no information about how "good" or "bad" the performance is, or where the border between acceptable and inacceptable values lies. To assess and interpret performance results, the Highway Capacity Manual (Highway Research Board, 1965) developed the concept of levels of service (LOS).

Levels of service

Levels of service (LOS) are designated ranges of values for a particular service measure, based on passenger's perception of a particular aspect of public transport service. LOS are expressed on a scale from A (highest) to F (lowest). The Transit Capacity and Quality of Service Manual by Kittelson & Associates Inc. et al. (2003) contains tables to convert values of different quality indicators into more comparable LOS values. While the LOS F is an undesirable condition from a passenger's point of view, the LOS A is not necessarily an optimal condition from the operator's point of view. In fact, it is not always possible to define an optimal level of service. In many cases, aiming for the highest LOS in a particular field can even be counterproductive, as agency resources are diverted to unproductive improvements instead of being used to improve service quality in areas where it is really needed. Generally, service providers should strike a balance between service quality and affordable service. This often leads to an optimum at intermediate levels of service in terms of quality (based on Kittelson & Associates Inc. et al., 2003, p. 3-22, 3-23). Depending on the challenges that a city's transport system is facing, the desired levels of service will vary greatly. For example a system that is designed to offer a maximum capacity at minimal cost will probably aim at lower LOS for the passenger load (and therefore the comfort criterion). To illustrate this with a fictitious example, the planners of a heavily used BRT system might find it useful to take out seats of the vehicles in order to accommodate more passengers. With fewer seats and the same amount of passengers, the load factor (p/seat) increases, leading to less available seats and therefore a lower comfort LOS. Apart from a higher per unit capacity, this measure may lead to shorter station dwell times, due to better circulation of boarding and alighting passengers, and therefore to shorter travel times (a higher LOS in commercial speed). Some differences in observed LOS are attributable to technical factors, whereas cultural differences may also play a role. In countries where public transport is the only affordable mobility option to people, much lower comfort levels of service (and therefore higher passenger loads) have to be accepted than in cases where passengers have the possibility to switch to private transport. Of course, the LOS has an influence on ridership and customer satisfaction. O'Sullivan et al. (1996) state that most passengers walk less than about 400 meters to a bus stop, whereas about the double of this distance is accepted for rail stations. Kittelson & Associates Inc. et al. (2003, p. 3-9) argue that bus services with a higher LOS could achieve an acceptance of walking access distances similar to rail-based transit. This could be achieved through more frequent services, a higher commercial speed, and more passenger amenities at stops. (section based on Kittelson & Associates Inc. et al., 2003 p. 3-2 & 3-3).

4.3.3 Quality criteria

It is not a straightforward issue to define the elements of a service that actually define its quality. Difficulties arise when the quality of modes or systems is to be measured and compared and when abstract terms like availability and accessibility have to be specified. Therefore, the number of definitions and listings of quality criteria in the literature is large and not conclusive. In the following, various sources of quality criteria will be presented to provide an insight into the subject and finally, an own list of quality criteria will be compiled.

Quality criteria by different authors

Weidmann et al. (2010, p. 123) list safety, security, speed, low user cost and punctuality as the primary interests of users. Kittelson & Associates Inc. et al. (2003 p. 1-7) state that users want a transport system to be available (operating at the right time and location), accessible, reliable, fast, comfortable, convenient, safe, secure and reasonably priced. Vuchic (2005, p. 529-534) offers a quite detailed discussion of passenger requirements for a transport system. He identifies availability as the basic requirement that people even consider to use a transport mode. Frequency, punctuality, and especially speed are listed as the most important elements influencing modal split and patronage. Comfort, convenience, security, safety and user cost are also identified as factors influencing the quality level from the user's point of view. Wright et al. (2007, p. 13) list the following key characteristics of excellence in public transport: ease of accessing a system, comfort of stations and vehicles, sense of system safety and security, legibility and clarity of system maps and signs, friendliness of staff and drivers, wide-spread recognition of system name and image, and overall cleanliness and professionalism. Another source of quality criteria of public transport services is the European Standard EN 13816 (CEN, 2002). In its annex A, it lists availability, accessibility, information, time, customer care, security, and environmental impact as quality criteria. For the specification of quality of service criteria in this work, the pattern established by EN 13816 has been followed to a large extent, but the work of the other above authors has also been included.

Synthesis of quality criteria and own selection

Because of the diversity in listings of quality criteria (see above), this work uses a particular selection of quality criteria for the purpose of assessing the quality of BRT systems and comparing BRT to other public transport systems. For example, the concept of reliability is listed as a separate quality criterion in this work, contrasting the quality criteria in EN 13816 – alongside with user cost, safety, and image (see Table 8). The elements of information and ticketing have been included into the criterion of accessibility since they influence the ability of passengers to access and use transport services. Contrasting the work of Vuchic (2005) and Kittelson & Associates Inc. et al. (2003), environmental impact has been included into the quality of service assessment since this aspect plays a role in the user's perception of the quality of a transport system. The quality criteria that are used in Table 8 correspond to the criteria in the quality of service definition from chapter 2.1.1. Table 8 includes indicators since some quality criteria, such as availability, are rather vague concepts and cannot be measured directly. The table briefly comments the problems that may arise if a quality criterion is not met sufficiently. This is to offer a clearer picture of what is meant by the quality criteria. Further reading on quality components, indicators, levels of service, and measurement methods is provided in Kittelson & Associates Inc. et al. (2003, p. 3-1 to 3-94).

Table 8 Quality criteria, indicators, and problems: the selection of this work

Quality criterion	Sub-criterion	Selected indicators	Potential quality problems
Availability	Spatial availability	- Area coverage measures - Average or cumulated distance to access or egress points	- Access points of the system are too far away from origins and destinations requested by users - Poor match between system layout and demanded travel relations
	Temporal availability	- Frequency / headway - Service span	- Scheduled departures / arrivals or operating hours do not coincide with the user's requirements - Waiting time is too long
	Physical availability	- Vehicle load factor	- Vehicles are overcrowded, passengers cannot get on
Accessibility	Information	- General information availability and quality - Provided travel information under regular and irregular conditions	- Users do not know where and when the service is available, what it costs, how the ticketing works, how long journeys take, etc. - Insufficient information in case of system failure, delay, etc.
	External interfaces	- Quality of pedestrian, bicycle, taxi and park & ride access	- Users have difficulties in physically accessing the transport system from outside
	Internal interfaces	- Ease of movement in the system - Quality of boarding, alighting & transfer facilities	- Movement inside the system and transfers from one means of transport to the other are difficult
	Ticketing	- Acquisition possibilities on and off system	- Acquisition of tickets is difficult or impossible, due to insufficient, complicated or defunct facilities
Travel time	Total actual duration of travel	- Commercial speed - System speed (summarised for all users) - Frequency / headway (affects average waiting time) - Quality of network layout (affects need to transfer)	- Journeys take considerably more time in comparison to alternative modes - Commercial or system speed is slow - Journeys require many transfers due to poor match between system layout and demanded travel relations - Average waiting times are too long

	Total perceived duration of travel	- Attractiveness of access and egress ways - Frequency, headway, punctuality, regularity (affects average waiting time) - Quality of network layout (affects need to transfer) - Travel time difference PT vs. car	- Journeys are perceived to take too much time due to poor attractiveness of access ways and interchange facilities - Journeys are perceived to take too much time due to frequent need to transfer with potentially long waiting times: waiting and transfer time is valued more negatively than in-vehicle time
Reliability	Dependability	- Percentage of services being provided as published	- Users cannot be sure that services always operate as published
	Punctuality (for scheduled services)	- Percentage of departures or arrivals being on schedule	- Users cannot be sure they arrive at the destination as scheduled - Connections are sometimes missed
	Regularity (for non-scheduled services)	- Degree of adherence to published departure intervals	- Users cannot be sure the service operates at regular intervals - Waiting time (and therefore travel time) varies considerably
User cost	Average costs of travel	- Costs of a trip of a given length or time period	- The service is too expensive in comparison to other modes or other everyday-life costs
	Ticketing options	- Availability of through ticketing - Flexibility of ticket system	- Purchase of several tickets is required for one journey - Lack of equality between fares (f. ex. flat fares for very short and very long distances)
Comfort	Cleanliness	- Overall cleanliness of vehicles and stops	- Users are not satisfied with the cleanliness of vehicles and stops
	Existence and usability of passenger amenities	- Quantity and quality of passenger amenities	- Users are not provided with the expected complementary facilities like luggage storage, toilets, commercial services, drink and food vending machines, trash containers, public telephones, etc.
	Seating and personal space	- Dimensions of seats and legroom - Overall availability of seats - Passenger load factor	- Seating is uncomfortable and does not provide sufficient space - Users do not find available seats - Standing passengers have difficulties to move
	Ride comfort	- Interior noise and vibration levels - Frequency and intensity of acceleration and braking	- Ride comfort is reduced due to high noise and vibration levels or uncomfortable acceleration and braking manoeuvres

	Ambiance	- Weather protection - Interior temperature and ventilation - Brightness - Quality of design	- Users are not protected suitably from adverse weather conditions - Unsatisfactory interior temperature and ventilation conditions - Poor lighting and design
Safety	Freedom from accidents	- Number of accidents per passenger kilometre	- Safety levels do not reach a satisfactory stage
	Emergency management	- Existence of emergency action plans	- Passengers and staff are not satisfactorily aware of actions to take in an emergency
Security	Actual freedom from crime	- Number of criminal incidents per passenger kilometre	- Actual security levels do not reach a satisfactory stage
	Perceived freedom from crime	- Availability of help points - Visibility & presence of monitoring and staff / police	- Perceived security levels do not reach a satisfactory stage - Users are afraid of using the service
Image	Public image of the service	- Popularity measurements	- Users do not feel confident when using the service or receive negative feedbacks from other individuals
Customer care	Customer interface	- Handling of enquiries and complaints	- Enquiries and complaints of customers are not treated satisfactorily
	Staff	- Availability, appearance, friendliness and skills of staff	- Users do not find staff or receive unsatisfactory or unfriendly service
	Assistance	- Quality of service offered to customers needing help	- Unsatisfactory or inexistent service for customers with special needs or at service disruptions
	Commitment and innovation	- Measures of customer orientation, innovation and initiative of the service operator	- Service operator is not perceived as being innovative and customer orientated - Service is not considered to be attractive and initiative
Environmental impact	Use of natural resources	- Exhaust, noise, vibration, visual impact, energy consumption etc.	- Service causes a disproportionally high impact on the environment - Users perceive service as being harmful to the environment

Factors influencing the quality of service

A look at the above indicators often clarifies which system elements of transport modes affect the quality criteria. Still, it is not always straightforward to determine which elements are responsible for the performance in terms of quality, and many factors influence more than one quality criterion. For example the route and network layout of a system affects not only its spatial availability, but also the travel time since the route structure determines the need of users to transfer from one route to another. Or the frequency of service is not only a measure for temporal availability, but also for travel time, since the average waiting time of users declines with a shorter headway between services. The level of segregation from other traffic directly affects travel time, reliability, comfort, and safety. Other quality criteria, in contrast, are largely independent of the mode-specific characteristics of a transport system, such as customer care or the cleanliness of vehicles. A more detailed assessment of factors influencing the quality criteria is provided in chapter 4.4 for the case of BRT systems. A general discussion of factors influencing quality of service can be found in Kittelson & Associates Inc. et al. (2003, p. 3-i to 3-93).

Defining the overall quality of service level

An assessment of the overall quality of service level of a system is achieved through a combination of all these quality criteria by a quality index. Yet, none of the above listings of quality criteria states the individual importance of the quality elements and thus how they should be weighted. A rough guideline for the weighting of quality elements is provided by Weidmann et al. (2010, p. 125). There, it is suggested that the importance of quality elements should be differentiated by trip length (urban vs. suburban transport) and trip purpose. In urban transport, the following quality elements are considered to be of special importance: frequency, accessibility, user cost, safety, and security. In suburban transport, the focus is on travel time, accessibility, punctuality, user cost, safety, and security. Vuchic (2005, p. 529) also states that users will tolerate low comfort levels on short, intra-urban trips, provided that the service is very frequent. On longer journeys, in contrast, a lower frequency may be tolerated, but a low comfort may deter passengers from using the service.

4.4 Quality levels of BRT systems

So far, the topic of public transport quality has been discussed from a general point of view, without considering peculiarities of different transport modes. In the following, the influence of BRT elements on the quality of service will be assessed. A special focus is placed on the influence of public transport priority measures and on the causes of unreliability in public transport. For more detailed information and specific system examples with a quantification of the impacts, see Diaz et al. (2009).

4.4.1 BRT dimensions and quality

Table 9 provides a general overview of the relevance of BRT dimensions regarding the above quality criteria. For example, the specification of a BRT system in the dimension of running ways influences its performance in travel time, reliability, comfort, safety, image, and environmental impact. This is because the segregation level of the running ways directly influences commercial speed, the interference with other traffic, and hence the need for braking and accelerating, fuel consumption, the risk of accidents, as well as the perceived modernity of a system. In general, it can be noted that most BRT dimensions influence not only one, but a number of quality criteria. In particular, the dimensions of running ways, stations, vehicles, and intelligent transport systems considerably influence the quality that is delivered to customers.

Table 9 BRT dimensions affecting quality criteria

		BRT dimensions						
		Running ways	Stations	Vehicles	Fare collection	Intelligent transport systems	Service and operations plan	Branding elements
Quality criteria	Availability		x			x	x	
	Accessibility		x	x	x	x		x
	Travel time	x	x	x	x	x	x	
	Reliability	x	x	x	x	x	x	
	User cost				x		x	
	Comfort	x	x	x		x		x
	Safety	x		x		x		
	Security		x	x				
	Image	x	x	x	x	x		x
	Customer care					x		x
	Environmental impact	x	x	x			x	

Source: Diaz et al. (2009 p. E5), modified.

Public transport priority, ROW and quality of service

One of the most important underlying factors influencing quality of service is the level of public transport priority and right of way (ROW). This factor is incorporated in the BRT dimensions of running ways (physical level of segregation) and intelligent transport systems (vehicle prioritisation). The element of vehicle prioritisation contains various levels. With passive signal timing measures, streets with public transport operation are simply assigned longer green phases. With active signal priority, approaching vehicles can actively extend or cause green phases. Obviously, the level of PT priority and the ROW characteristics influence travel time by affecting the commercial speed of a system. Besides, they affect reliability by lowering interference with other traffic (in particular with car queues) and thus the susceptibility for delay propagation and vehicle bunching. The criteria of comfort, safety, and environmental impact are also influenced, because less interference and conflicts with other traffic do not only reduce the risk for collisions, but also the need for braking and acceleration manoeuvres, which in turn influences fuel consumption, noise, and pollution. Apart from having an impact on the quality of service, PT priority and ROW also have a significant impact on operating costs, as it will be demonstrated in chapter 5.3. Vuchic (2005, p. 111-114) concludes that increasing the ROW level significantly increases speed, reliability, schedule adherence, and PT patronage due to diversion of car users. The measure reduces user travel time, and by lowering fleet size and required manpower, it lowers operating costs. It also has impacts on street congestion, which are positive or negative, depending on whether the PT lane is added to or subtracted from the existing street space. In general, Vuchic states that higher ROW levels require higher investments, but offer a significantly higher quality of service and considerably lower operating costs.

Independent quality criteria

Interestingly, it can be noted that the important quality element of user cost is not directly influenced by most BRT dimensions since the pricing of services is often rather a result of political considerations and is not necessarily related to the system costs. In the extreme case, user cost can be completely unrelated to system costs, when a system is free of charge out of political considerations, such as the bus rapid transit system EmX in Eugene (Oregon, USA). Also the quality criterion of customer care has little or nothing to do with the BRT system specification. The quality of customer care rather depends on other factors, such as the operator's internal processes as well as the availability and skills of the staff. Apart from these general observations, each quality criterion will be analysed more thoroughly in the following. In the cases where quantitative analysis is delivered, the raw data originate from the same sources as in chapter 3, namely Diaz et al. (2009) and Wright et al. (2007). The author of this work wishes to highlight again that the raw data are of quite mixed quality. They have been checked for plausibility and reviewed accordingly, but a thorough revision and verification of the data would go beyond the scope of this work. The main idea here is not to provide exact values for each system, but to convey a general picture by using a wide variety of system examples.

4.4.2 Availability

Availability is the key element when deciding whether or not a transport service is even an option for a trip. If the point of access to a transport system (i.e. the station) is too far away from where a potential passenger wants to start his or her trip, or if the service is not running more or less at the desired time of the day, the user will not consider using the service, even if it is free of charge, travels at a high speed and offers an extraordinary comfort. In addition, the vehicles must provide enough space for a passenger to board; otherwise the service is not physically available to him or her. This is even more relevant for passengers with disabilities or special needs. For example, a transport system is only available to a wheelchair user if there is actually enough space in the vehicle for the wheelchair.

Availability of BRT systems

The spatial availability of a system is influenced mostly at early planning stages, when the network is laid out and stations are positioned. Short average station spacing favours spatial availability since it reduces the distances for users to access/egress point. In turn, short station spacing reduces travel speed due to more frequent stopping. Figure 9 lists the average station spacing for different BRT systems and for the averages of the previously identified BRT classes. Heavy infrastructure and understatement BRT have the shortest average station spacing of about 700 m, whereas this figure is about 800 m for BRT light and 1000 m for intelligent BRT. However, these figures do not mean that heavy infrastructure and understatement BRT are best in terms of spatial availability. On the contrary, heavy infrastructure BRT systems that operate mainly in the principal corridors of a city are less able to provide dense area coverage than conventional bus systems or understatement BRT systems that tend to form networks. Hence, corridor-based BRT or rail systems mostly rely on feeder routes to provide sufficient spatial availability. Temporal availability is largely influenced by service and operations plans. Short headways, as observed in most BRT systems, lead to short waiting times and to arrival times that coincide with the users' requirements. To provide the same line capacity as rail systems, bus systems with a lower capacity per vehicle need to provide more frequent services. This leads to a relatively good temporal availability of bus systems in comparison to higher capacity rail systems. Of course, the provision of a higher frequency also implies potentially higher operating costs, since more vehicles are required. Intelligent transport systems help to manage the operation in the event of irregularities and thereby help in avoiding that services have to be suspended due to disruptions. By this means, the use of ITS technology has a positive impact on the average availability of the transport system.

4.4.3 Accessibility

According to Table 8, accessibility does not only include the ease of physical movement in the system, but also the provided travel information and the possibilities to acquire and validate tickets. Primarily, the configuration of stations and vehicles determines the physical accessibility of a public transport system.

Accessibility of BRT systems

One important element to ease physical movement in the system is the provision of level access from stations to vehicles. Most heavy infrastructure BRT systems use high-floor vehicles and platforms, whereas intelligent BRT or BRT light systems often rely on low-floor vehicles and slightly elevated sidewalks. Another aspect of accessibility is the need of users to acquire or validate a ticket within a reasonably short time and in the simplest possible way. Consequently, the BRT dimension of fare collection influences the accessibility of a system by specifying the ticket acquisition possibilities and the fare structure. Flat and easily understandable fare structures favour accessibility together with an appropriate selection of payment options. Intelligent BRT and heavy BRT systems use the most sophisticated payment options with transport agency-issued contactless smartcards, through commercial credit or debit cards, or even through personal mobile communication devices. BRT light systems mostly rely on ticket-issuing machines or cash payment. The selection of the most appropriate payment option has to be made with regard to the local context. For example, the use of mobile communication devices as a payment option only makes sense in cities where most users actually possess such devices. For example the trolleybus system in Quito (Ecuador), a heavy BRT system, uses a very simple ticketing approach, where users access the stations simply by inserting a coin into a fare box. Remarkably, the issuing of smartcards has proven to be successful in other Latin American cities, such as Bogotá (Colombia). In general, a system that incorporates the most appropriate payment option for the local context has the highest degree of accessibility in terms of ticketing.

BRT systems and user information

Furthermore, users need to know where and when a service is available, what it costs, and how long journeys take. Therefore, information is another important aspect of accessibility. Figure 8 shows an example where the use of intelligent transport systems (ITS) provides users with information about the availability of a bus service in regular service and in the case of service disruptions. In this case, users are not only provided with the information of when the next service is available, but also if the service is running at regular intervals (the last line indicates that the service currently runs at irregular intervals), and if the next vehicle is equipped with wheelchair access.

Figure 8 Customer information (and unreliability) on the Zürich bus line 69

With this information, the system becomes easier to use and thus more accessible to users. The use of branding elements can also improve access, for example if users are able to find and identify the stations of a system more easily from a distance because of recognizable signposts and identity features. The use of branding elements is mostly found in heavy and intelligent BRT systems. Intelligent BRT systems use both ITS technology and branding elements whereas understatement BRT systems rely only on ITS and are normally not branded and identified as a special tier of service.

4.4.4 Travel time

The criterion of travel time is the most important single characteristic influencing modal split (Vuchic, 2005). Travel time contains not only the time spent in a vehicle but also the time needed to access and egress the system, as well as waiting and transfer time. As a result, travel time does not only depend on commercial speed (also named operating speed) even though it is arguably the most important lever to improve (i.e. decrease) average travel time. Other factors influencing the average travel time of users are network coverage (dense networks require less time for average access and egress), network layout (a better layout reduces the need to transfer), and frequency of service. Further, it is important to note that the components of travel time experienced by users are not valued equally. Accordingly, there is a considerable difference between actual and perceived travel time. A review of the users' valuation of in-vehicle, access and waiting time in the context of Great Britain can be found in Wardman (2004). Vuchic (2005) states that waiting time is weighted 1.5 to 2.5 times more heavily than in-vehicle time. The users' valuation of waiting and access time depends on the attractiveness of the access ways, topography, and weather conditions. Following the complex nature of the travel time criterion, there are various ways to influence this quality criterion and the approaches vary considerably between BRT classes.

BRT dimensions influencing travel time

The actual and perceived travel time experienced by users in a transport system is determined at the stages of both strategic and tactical planning when the area coverage, network layout, frequency of service, and connections between services are defined. As illustrated in Table 9, all BRT dimensions (except the branding elements) influence travel time; mostly by affecting commercial speed. Vuchic (2005, p. 98) highlights that the importance of commercial speed should not be underestimated and that operators should make every operationally and economically feasible effort to increase commercial speed. Therefore, the elements influencing commercial speed are discussed in more detail below. However, the BRT dimensions also influence the other elements of travel time. For example, the specification of the service and operations plan has an influence on travel time since average waiting times decline along with an increasing frequency of service. Perceived travel time is also reduced by more convenient stations and vehicles because the valuation of waiting and transfer time is less negative in user-friendly environments. Customer information also reduces perceived travel time since users know when the next service arrives and can use the waiting time more productively.

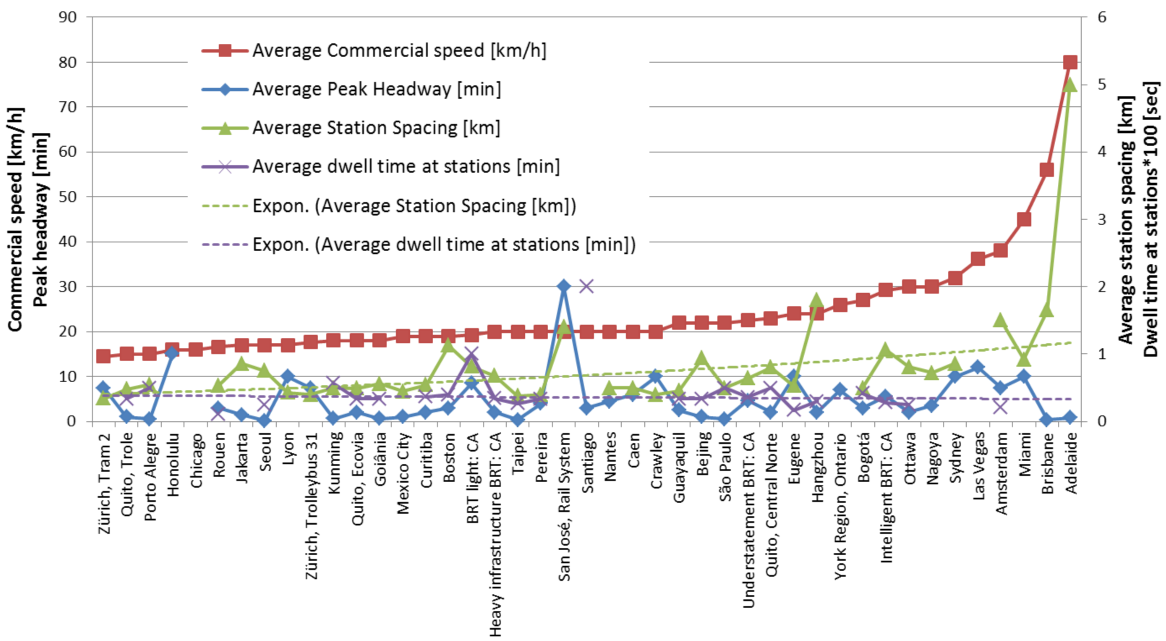
Increasing commercial speed

A detailed discussion about measures to increase commercial speed is provided by Vuchic (2005, p. 98-114). In his analysis, Vuchic states that commercial speed has not only a major impact on performance, but also on operating costs and the role of public transport in a city. Increasing commercial speed of public transport leads to shorter travel times for users and to a reduction in the operating costs when cycle speed is increased so fleet size can be reduced while providing the same frequency of service. Thus, commercial speed is not only important to users, but a higher commercial speed can also imply a reduction in the required fleet size and manpower, and hence lower operating cost to the operator as well as lower subsidies by the community. Vuchic mentions a number of general measures to increase commercial speed, disregarding the transport mode. These measures include specialized vehicle design (low floors, wide doors etc.), propulsion technology, intersection and street design, introduction of public transport lanes, traffic signal priority measures, increased station spacing, appropriate station design (level access), and elements of public transport operation, such as faster fare collection procedures and the introduction of express routes. Not surprisingly, this list of measures strikingly resembles the actual definition of the bus rapid transit mode. This observation illustrates the fact that a main idea of the BRT mode is to increase commercial speed in comparison to conventional bus operation. Some measures in vehicles, such as the use of double-channel doors and low-floor entrances do not only increase commercial speed, but also accessibility, reliability and comfort by minimising the time and effort needed for users to enter and leave a vehicle. Additionally, improvements in stations and running ways play a major role in reducing travel time. White (2002, p. 53) states that up to a third of bus journey time is spent at passenger stops and traffic lights. Therefore, he suggests “appropriate ticketing and boarding systems” as a measure to reduce station dwell time and promotes signal priority to reduce time spent at traffic lights even though this might reduce overall intersection capacity for the remaining traffic.

Commercial speed of BRT systems

The commercial speed of various BRT examples is presented in Figure 9.

Figure 9 Station spacing, headway, and station dwell time compared to commercial speed



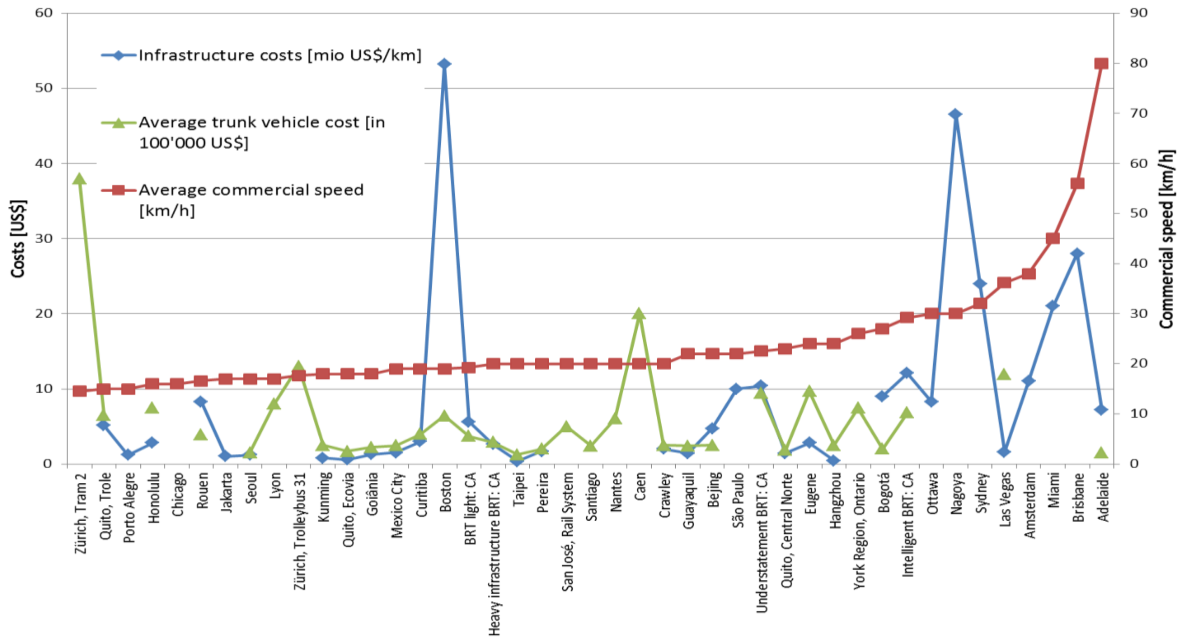
Data sources: Diaz et al. (2009), Wright et al. (2007). CA = cluster average

First of all, it can be noted that about half of the analysed BRT systems have quite similar, low commercial speeds between 15 and 20 km/h. Only few systems have commercial speeds above 30 km/h. The systems of Brisbane and Adelaide are special cases where very high commercial speeds are achieved mainly by large distances between stations, even though very short headways are maintained. The systems of Ottawa, Nagoya, Sydney, Las Vegas, Amsterdam, and Miami are amongst the systems with the highest commercial speed and all of them show relatively high values in average headway and / or average station spacing. The correlation between average station spacing and commercial speed is also illustrated by the dotted green exponential regression line. No (negative) correlation between average dwell time at stations and commercial speed can be observed. In fact, the values for average dwell time at stations are quite similar for all systems, apart from the system of Santiago (Chile). It could not be verified if this outlying value is an error in the raw data (Wright et al., 2007, p. 774, indicating an average station dwell time of 1-3 minutes) or has another explanation. In general, it can be concluded that intelligent BRT systems achieve the highest average commercial speed of all BRT classes mainly by using the longest average station spacing. Other reasons for the relatively high commercial speed of intelligent BRT systems can be the use of ITS technology and thus vehicle prioritisation, the off-board fare collection process, and the specialised vehicles allowing faster boarding, alighting, acceleration, and braking. Understatement BRT systems have the second highest commercial speed by relying mostly on the use of segregated running ways and to some extent also on ITS technology. Heavy infrastructure BRT systems have a considerably lower average commercial speed in spite of using heavily separated busways. This can be explained by a combination of factors, such as the widespread lack of ITS technology, the short peak headway causing congestion in the busway and the short average station spacing. BRT light systems have an even lower average commercial speed in spite of longer average station spacing than heavy BRT. A possible explanation for the low average commercial speed of this class is the frequent lack of segregated busways, the high frequency of service, or by the use of standard vehicles, stations, and fare collection procedures leading to slow boarding and alighting procedures. Accordingly, BRT light systems have by far the highest average dwell time at stations.

Investment costs and commercial speed

Another hypothesis is that the commercial speed of a system can to some extent be explained by the level of investment costs. This is in accordance with the argument by Vuchic (2005, p. 525) that the costs of a system are mostly dependent on their type of ROW. Hence, a higher level of investment in infrastructure, and thus in running ways, should imply a higher degree of separation from other traffic, and hence a higher operating speed. However, Figure 10 illustrates that there is no clear evidence supporting this hypothesis even though intelligent BRT and understatement BRT have both significantly higher average operating speeds and higher investment costs than heavy BRT and light BRT. The higher cost and speed of intelligent BRT and understatement BRT should be interpreted with care since the picture is distorted by many extreme outliers in cost and speed. Especially the BRT systems of Boston, Nagoya, Sydney, Miami and Brisbane (all intelligent or understatement BRT) have very high infrastructure costs, due to special conditions such as bus tunnels (Boston), expensive guidance technology (Nagoya), or grade-separated busways on freeways (Miami). No correlation can be found between system speed and average trunk vehicle costs.

Figure 10 Commercial speed compared to system costs



Data sources: Diaz et al. (2009), Wright et al. (2007).

4.4.5 Reliability

The quality criterion of reliability can be divided into dependability, punctuality, and regularity of services. Dependability measures the percentage of services being provided as published during a given time period. Punctuality (also named on-time performance or schedule adherence) is the most widely used reliability measure in services with a low frequency (Kittelson & Associates Inc. et al., 2003, p. 3-45). Regularity (or headway adherence) is the most important reliability measure when services run at more frequent intervals. Then, punctuality is of minor importance than headway regularity since users want to avoid vehicles to arrive in bunches with overcrowded lead vehicles and longer waits between bunches. The phenomenon leading to vehicle bunching is called delay propagation. When it occurs, regularity, punctuality and commercial speed sharply decline due to longer station dwell times of the delayed lead vehicle. Average waiting and travel time rise substantially for users. This chapter will discuss delay propagation and common causes of unreliability, and subsequently analyse BRT classes for their performance regarding reliability.

Delay propagation

White (2002, p. 54) illustrates the phenomenon of delay propagation with an example: he describes a model corridor, where the average waiting time for vehicles at each intersection with traffic lights is scheduled to 20 seconds. If a bus just misses a green phase, or gets caught in a car queue for 80 instead of 20 seconds, it arrives at the next station with a delay of 60 seconds. Because of this late arrival, more passengers than usual will have accrued at the next station if an approximately random afflux of passengers is assumed, as it is normally the case for services with short headways. The additional passengers extend the time needed for boarding and alighting at the second station and thus cause further delay. A second bus, departing 3 minutes after the first from the initial station, encounters fewer passengers than usually at the second station since the first bus has passed later than scheduled. White concludes that after only four stations and two intersections where the first bus misses the green phase, while the second bus only waits the scheduled 20 seconds, headway has diminished from the initial 3 minutes to only 45 seconds. The risk for delay propagation increases with a higher degree of interference with other traffic (i.e. insufficient vehicle prioritisation), more sources of unpredictable interference (such as ticket vending by the driver or simply higher numbers of passengers at stations), and shorter average headways. An extreme case of vehicle bunching is illustrated in Figure 11.

Figure 11 An extreme case of vehicle bunching and delay propagation in Kiev (Ukraine)

Image source: www.subways.net (unknown year)

Causes of unreliability

Vuchic (2005) states that reliability is directly related to the degree of traffic interference, and thus to the ROW category. In other words, the main cause for unreliability in public transport is interference with other traffic, or even with other public transport vehicles, if average headways are too short. Reliability can be improved by a higher degree of public transport priority and segregation from other traffic, as well as by changing to higher capacity modes in the cases where headways are below a critical threshold. Bruun (2005, p. 20) locates this critical threshold at about 3.5 minutes headway for bus systems. He states that in practice, headways below 3 to 4 minutes complicate the implementation of signal priority, and a suitable commercial speed becomes difficult to maintain. A practical example quantifying public transport reliability is provided by Carrasco (2011) for the bus line 31 in Zurich. His results indicate that in this case, intersections contribute most to delays on the bus line, even with the presence of active signal priority for public transport vehicles. He states that vehicle priority measures at intersections, holding strategies, and timetables with sufficient recovery times contribute most to a stable operation and the relatively high reliability levels in Zurich, despite the limited level of segregation and exclusive lanes. Further, he concludes that no significant improvements in reliability can be expected without a higher degree of segregation from other traffic.

Reliability of BRT systems

The above analysis of the causes of unreliability in public transport has shown that a higher level of segregation of running ways can contribute to reliability improvements in bus systems. Hence, heavy infrastructure BRT and understatement BRT should perform well in terms of reliability since running ways are largely segregated from other traffic in these BRT classes. The use of ITS technology also contributes to increasing the reliability of BRT systems in comparison to conventional bus systems. The use of vehicle prioritisation reduces the risk of delay propagation, and operations management technologies allow for more advanced holding strategies and active vehicle dispatch by an operations control centre. The use of ITS technology is at the highest level in the cases of intelligent BRT and understatement BRT. However, too short headways are an important issue in various existing BRT systems since all four BRT classes contain examples with average peak headways well below 1 minute. In these cases, the probabilty is high that reliability is not at the desired level, especially during peak hours. Reliability improvements could in these cases be achieved by changing to transport modes with a higher capacity, or by constructing parallel transport corridors. Changing to higher capacity modes could also imply cost advantages in the case of high demand levels, especially in the case of rising local labour cost levels, as will be demonstrated in chapter 5.3.4. Other measures against unreliability and delay propagation are passing facilities at stations, as they are implemented in some heavy BRT systems, or operational practices, adequate timetables, and disposition concepts at the level of operational planning, as demonstrated in chapter 4.2.2. In short, heavy BRT systems rely mostly on physically segregated running ways to improve reliability, whereas intelligent BRT use ITS technology, and understatement BRT use both measures.

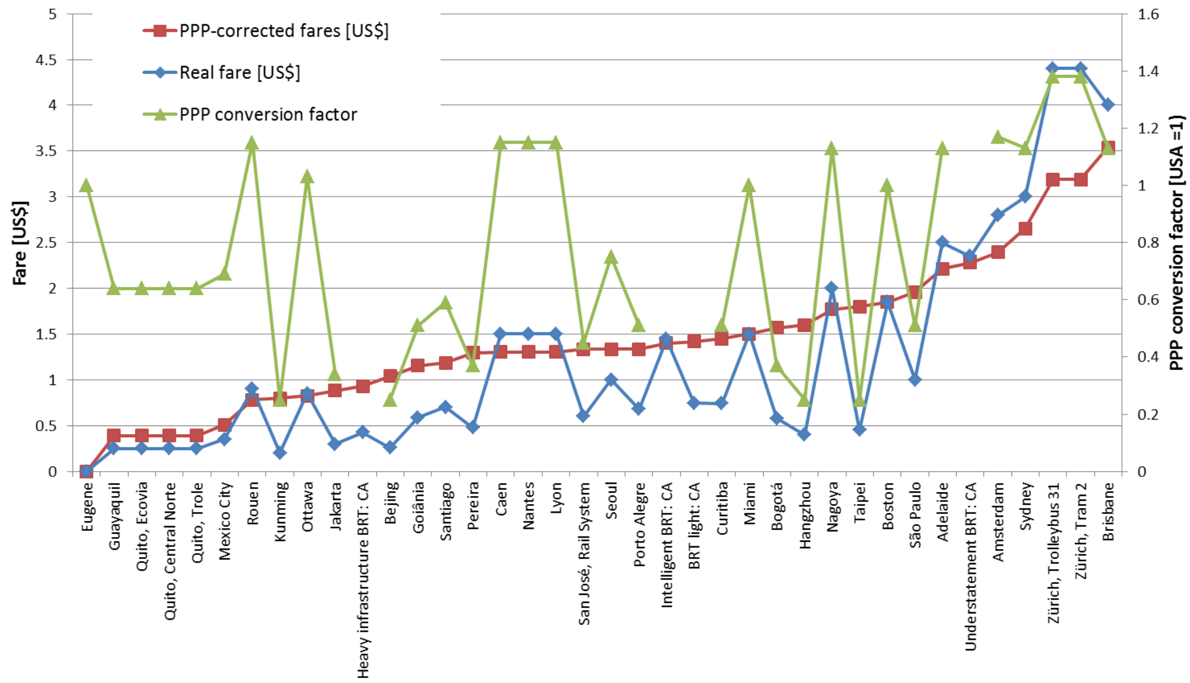
4.4.6 User cost

As profit maximising individuals, users wish to find a public transport system that offers them a suitable level of performance at a minimal cost. Since public transport is mostly not the only alternative to travel, the costs incurred to users have direct consequences for the demand. If all the other performance elements are held constant, demand drops with an elasticity of ca. -0.2 to -0.3 in relation to fare changes in urban public transport (Vrtic et al., 2000). Price fixing in public transport is therefore a delicate issue that directly influences patronage of PT systems and the modal share. Because public transport is generally not the market leader in short-distance surface travel, fares in public transport are not primarily fixed according to the costs incurred for providing the service, but based on the costs of the competing private traffic, or even based on political considerations (based on Weidmann, 2008, p. 52). According to Table 9, the only BRT dimensions directly influencing the costs incurred to the user are fare collection and service and operations plan. The fare collection procedure influences user cost for example by the ability of payment facilities (i.e. ticket vending machines etc.) to differentiate between fares (flat fares vs. spatially and temporally differentiated fares). Differentiating the fare structure allows users a greater degree of fairness in the fares, but complicates the issue of providing information, and thus the accessibility of a system. Differentiated fares might also increase operating costs if expensive ticketing facilities are required instead of simple ones. Similar considerations apply for the dimension of service and operations plan since for example the zoning of a served area influences the cost incurred to the users. Yet, when a city upgrades a transport system to provide more comfortable and more expensive services, authorities may decide to fix the fares at a higher level. Though, this observation is not directly related to BRT dimensions, but rather to political and financial valuations of the community, and will therefore not be discussed further here. The following figures undermine these findings by analysing the empirical BRT data for the influence of various factors on user cost.

Fares in BRT systems

Figure 12 provides an overview of current data on fares in different systems. Since the systems are operating in very different national contexts, they are corrected here by a purchasing power parity conversion factor, using the USA level of purchasing power as a reference

Figure 12 Real and purchasing power parity corrected fares



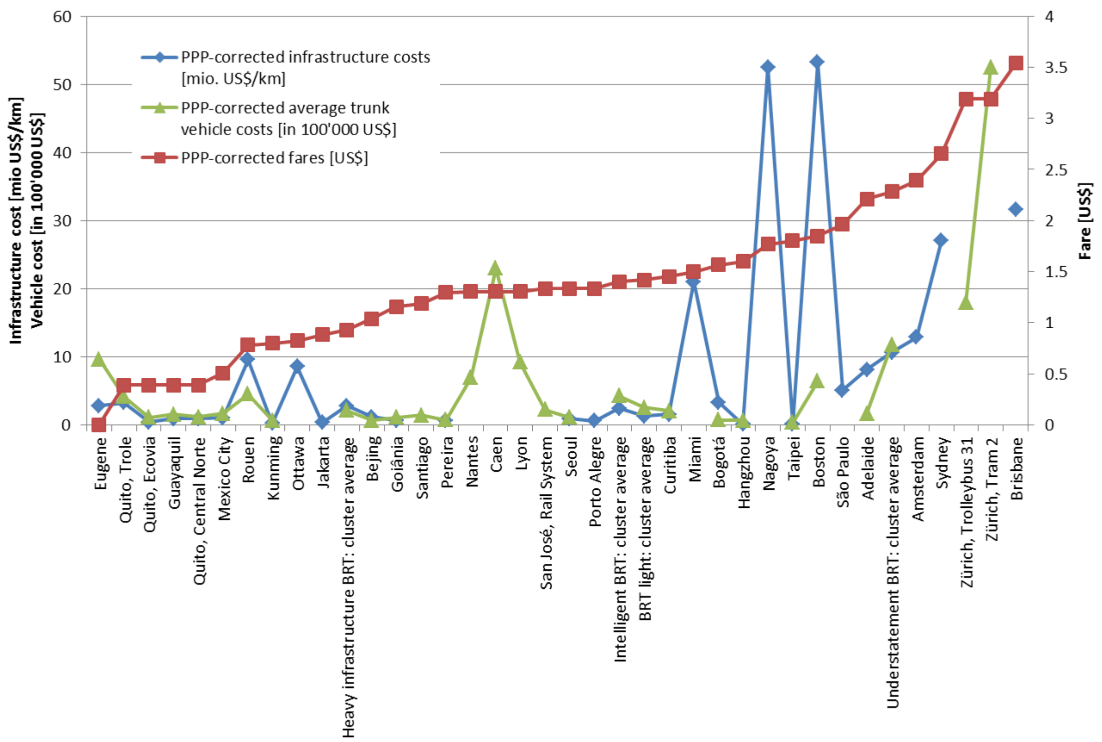
Data sources: Diaz et al. (2009), Wright et al. (2007).
Conversion factor: Nationmaster.com (2011).

It can be noted that fares vary considerably even when corrected for purchasing power. The lowest fares compared to purchasing power (apart from the free system in Eugene, Oregon) are found in Ecuador and Mexico City. In these cases, prices are fixed merely by political authorities, and not on the basis of real system cost and revenue (Hidalgo et al., 2010a, p. 28). In cases where this political price fixing occurs, the inherent characteristics of public transport systems have a very limited (or no) influence on user cost.

System costs and user costs

Figure 13 provides a direct comparison of purchasing power parity (PPP) corrected fares and BRT system costs to analyse how strongly the capital costs of BRT systems influence the respective costs incurred to users (i.e. the fares). One hypothesis in this case is that systems causing higher capital costs for the community (through expensive infrastructure and vehicles) are more expensive to users. To analyse this hypothesis, especially the systems of Rouen, Nantes, Caen, and Lyon (France) are worth noticing. In these cases, the PPP corrected fares are well below 1.5 US$, despite of relatively high infrastructure and vehicle costs. On the other hand, in the cases of Curitiba, Bogotá, Hangzhou, Taipei, and São Paulo, the PPP corrected fares are between 1.5 and 2 US$, whereas the infrastructure and vehicle costs are much lower compared to the French examples. From the analysis of the below empirical data, it can be concluded that the fares of existing BRT systems in fact seem to be largely independend of the capital costs of a system. Still, the above hypothesis receives weak support by the fact that both the systems with the highest fares and the systems with the highest infrastructure and vehicle costs are found towards the same (right) side of the below diagram. Even when corrected for purchasing power, the most expensive systems in terms of both capital and user costs are found in industrialised countries, such as Australia, the Netherlands, and Switzerland. Accordingly, the average fares and system costs of understatement BRT systems, which are mostly operating in Europe and North America, are higher than the average of heavy infrastructure BRT systems, operating mostly in South America and Asia. The outlying cost values in the examples of Miami, Caen, Boston, Nagoya, Sydney, Brisbane, and Zürich are mainly explained by extraordinary situations, such as bus tunnels or particularly specialised vehicles. In any case, it is important to notice that this analysis only considers capital costs and not operating costs.

Figure 13 Purchasing power parity corrected fares and system costs

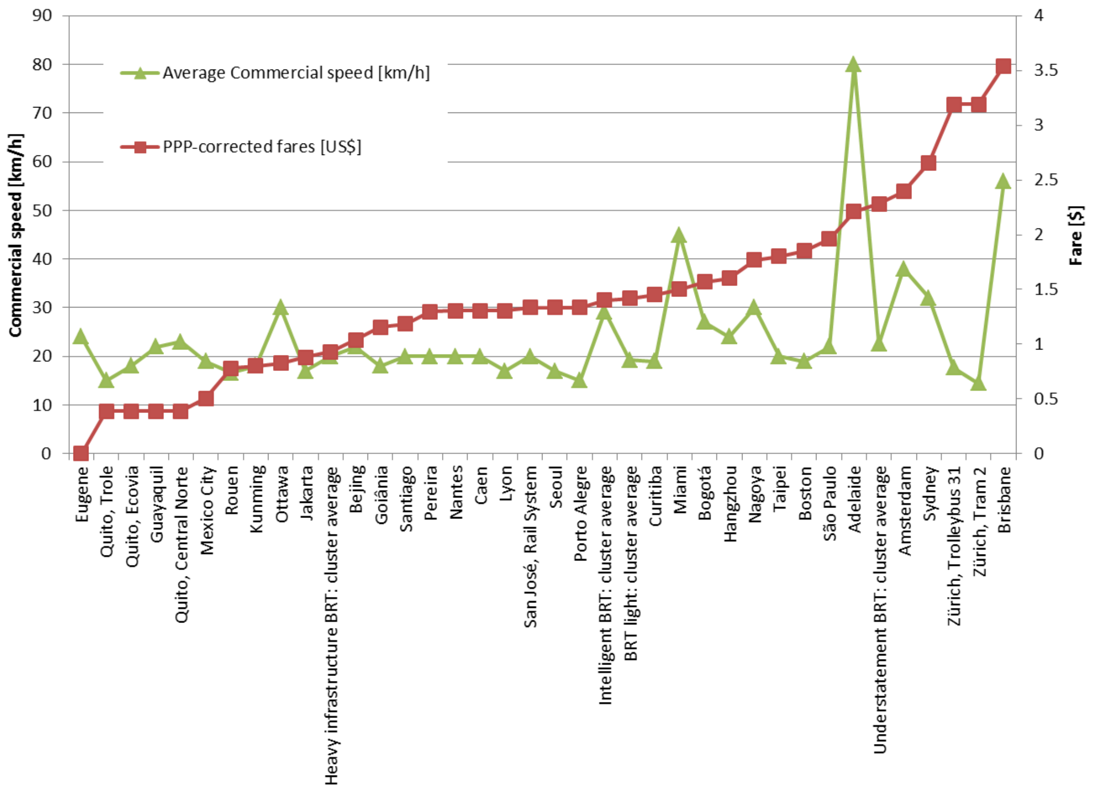


Data sources: Diaz et al. (2009), Wright et al. (2007), Nationmaster.com (2011).

Quality and user costs

Another hypothesis is that the fares depend on the quality of service level provided by a BRT system. Since the data considered in this work provide very limited information on quality of service, commercial speed is used as an approximation here since it has been identified as a key element of service quality. Yet, the comparison between fares and commercial speed in Figure 14 shows that there is no clear relation between the two.

Figure 14 Commercial speed and purchasing power parity corrected fares



Data sources: Diaz et al. (2009), Wright et al. (2007), Nationmaster.com (2011).

4.4.7 Comfort

In Table 8, the comfort criterion encompasses the elements of cleanliness, existence and usability of passenger amenities, seating and personal space, ride comfort, and ambiance. These elements include the overall availability and dimensions of seats, the ability of standing passengers to move, interior temperature, ventilation, noise and vibration levels, and thus the chance for users to enjoy a relaxed travel experience. However, not all of these elements depend directly on the choice of a transport mode. For example, the element of cleanliness is largely independent of whether a bus- or a rail-based mode is used. Other aspects, such as passenger amenities, seating and personal space, ambiance, the ease of boarding and alighting, interior noise, temperature, and ventilation are influenced by the specifications of the vehicles and stations and thus indirectly by the choice of mode. Of course, the BRT systems with enhanced vehicles and stations aim at achieving higher quality levels in terms of comfort. Particularly heavy infrastructure BRT systems often feature comfortable and weather-protected stations, sometimes even terminals with a large variety of passenger amenities. The stations mostly allow level boarding and alighting through an exact match between platform height and the vehicle floor. This characteristic does not only influence comfort (passengers do not have to climb stairs when entering a vehicle), but also accessibility (especially for passengers with mobility impairments), travel time, and reliability by reducing station dwell time due to a quicker boarding and alighting procedure. One of the most distinguishing features of intelligent BRT systems are the qualitatively enhanced vehicles that aim at providing increased seating comfort, personal space, and riding comfort, as well as improvements in the ambiance by enhanced design and lighting. BRT light and understatement BRT do not provide substantially higher comfort levels than conventional bus operation since these classes mostly use standard vehicles and stations.

4.4.8 Safety

The criterion of safety is largely independent of the BRT class. Possibly, the enclosed and often guarded stations of heavy infrastructure BRT systems and the enhanced vehicles (often with video monitoring) found in intelligent BRT systems show some slight (actual of perceived) safety improvements in comparison to BRT light, understatement BRT, and conventional bus operation.

4.4.9 Security

The level of security, understood as the freedom from accidents, mainly depends on the level of segregation from other (motorised and non-motorised) traffic. Hence, the BRT systems with the most segregated running ways should provide the highest levels of security, i.e. heavy infrastructure BRT and understatement BRT.

4.4.10 Image

The public image of a transport service influences both the quality of service perceived by users, and the mobility behaviour of the population. Most systems in the heavy infrastructure BRT and intelligent BRT class, as well as some BRT light systems, make considerable efforts in the dimension of branding elements in order to create a favourable public image.

Image, ridership and the rail bonus

Scherer (2011) analyses the existence of a “rail bonus” and the sources of potentially higher preference for rail-based systems in comparison to bus systems in the Swiss context. She states that the public image of a transport system has an impact on demand, but that the factors influencing this public image are not always clear and tangible. Scherer’s findings indicate that in the Swiss context, only the group of frequent public transport users show a significant preference for tram above bus systems. She identifies “free flow” and environmental friendliness as the aspects being rated significantly higher for tram than for bus systems. The rating of “free flow” is mainly explained by the higher ROW category and dedicated running ways of tram systems, whereas the perceived environmental friendliness can be attributed to the electric propulsion technology. Another finding by Scherer is that the bus mode is analysed more rationally than a tram. She concludes that these (mostly positive) affective emotional aspects are relevant for the image and hence influence mobility behaviour.

The image of bus rapid transit

If the above findings hold as well for the case of BRT, the higher ROW category and the more environmental friendly propulsion technology that are found in many BRT examples should help to generate a better public image of bus rapid transit in comparison to conventional bus systems. Cain et al. (2009) found that in the perception of general public, bus rapid transit can even compete with light rail transit (LRT) systems. This high valuation of the image of BRT systems by the public is confirmed by Currie (2005), presenting empirical evidence that BRT systems can be as effective in attracting passengers as heavy and light rail. In general, BRT systems with higher quality levels, and most importantly with a high degree of segregation from other traffic and environmentally friendly propulsion technologies, are assumed to have clear advantages above conventional bus systems in terms of the public image. In particular, the higher image of intelligent BRT systems could be explained by the use of clean vehicle technology, branding elements, and a generally high quality level. Heavy infrastructure BRT systems rely on largely segregated running ways, branding elements, and also a high general quality level to generate a positive image. The use of branding elements is much less common in the case of BRT light systems, since the quality levels of these systems do not always allow for the generation of a significantly better image than the one of conventional bus systems. Understatement BRT systems do not use branding elements and potential advantages in their image are purely attributable to other quality improvements.

4.4.11 Customer care

The criterion of customer care is largely independent of the transport mode or BRT class, and will thus not be discussed further here.

4.4.12 Environmental impact

A discussion of the environmental impact of BRT systems can be found in Diaz et al. (2009, p. 4-36 to 4-44). These authors identify local air pollutants, greenhouse gases, fuel economy, noise, and visual impacts as main indicators of environmental quality that are influenced by BRT operation. The above authors identify the following factors that have an influence on these environmental indicators: vehicle propulsion technology, generated mode shift (i.e. avoided car trips), traffic system improvements (i.e. congestion relief), vehicle size, frequency of service, running way paving material, land use and severance due to station and running way construction. Hence, it can be argued that in broad terms, intelligent BRT with advanced vehicle and propulsion technologies should perform better in terms of air pollution and noise, whereas understatement BRT and BRT light have smaller differences to the performance of conventional bus systems. In terms of visual impact, BRT light and intelligent BRT should perform better, since they rarely feature segregated running ways and large stations.

4.4.13 Synthesis: quality levels of BRT systems

Table 10 summarises the above discussion. Performance characteristics of the four BRT classes regarding each quality criterion are presented in keywords, and the colours roughly indicate the performance levels. The red, blue, and green colours respectively indicate a low, medium, and high level of performance. From this rough overview, it can be extracted that BRT light performs low or medium in all quality criteria. Hence, its quality improvements compared to conventional bus services, and therefore the inclusion of these systems into the BRT label must be questioned. Understatement BRT is the only class with a high level of availability and reliability. Hence, a system similar to the examples of this BRT class could be an alternative for cities wishing to improve conventional bus service in terms of availability and reliability, without upgrading to the more capital cost intensive solutions of heavy infrastructure and intelligent BRT. In fact, the efforts of many cities to improve reliability and commercial speed of their bus networks by constructing exclusive running ways and introducing ITS technology have led to systems similar to the understatement BRT category. For example, the city of Zurich (Switzerland) has made such efforts to improve its public transport system, and not surprisingly, the Zurich example has been identified as an understatement BRT system by the cluster analysis in chapter 3. Both heavy BRT and intelligent BRT provide substantial improvements in accessibility, comfort, safety, and image, whereas intelligent BRT is the only system with considerable improvements in travel time and environmental impact. Probably, users of the heavy infrastructure BRT systems in cities like Quito (Ecuador) or Bogotá (Colombia) would argue that the BRT system has brought significant advantages in travel time and environmental impact compared to the previous systems. This might be true, but if these heavy infrastructure BRT systems are compared to well-functioning non-BRT standard bus systems (such as in Zurich, Switzerland), their performance in terms of travel time and environmental impact is at a very similar level. The main quality differences to well-functioning non-BRT systems are in the criteria of accessibility, comfort, safety, and image.

Table 10 BRT classes and quality criteria

Quality criteria	BRT class: BRT light	BRT class: Heavy infrastructure BRT	BRT class: Intelligent BRT	BRT class: Understatement BRT
Availability	Medium station spacing Mostly network-based	Short station spacing But: mostly corridor-based	Long station spacing Low frequency of service	Short station spacing Mostly network-based
Accessibility	Low-floor vehicles Ticket-issuing machines	High-floor vehicles and level platforms Modern payment options	Low-floor vehicles Modern payment options Customer information focus	Customer information focus But: standard vehicles, stations & fare collection
Travel time	Medium average station spacing But: lack of segregated busways, high frequency, standard vehicles, stations, and fare collection	Segregated running ways Off-board fare collection But: lack of ITS technology, high frequency and short station spacing	Long average station spacing ITS technology (vehicle prioritisation) Off-board fare collection Specialised vehicles	Segregated running ways ITS technology (vehicle prioritisation)
Reliability	Few special measures	Segregated running ways	ITS technology (vehicle prioritisation and operations management)	Segregated running ways ITS technology (vehicle prioritisation and operations management)
User cost	Medium PPP-corrected fares	Lowest PPP-corrected fares	Medium PPP-corrected fares	Highest PPP-corrected fares
Comfort	Few special measures	Comfortable and weather-protected stations with level access	Enhanced vehicles: seating & riding comfort, personal space, design, and lighting	Few special measures
Safety	Few special measures	Enclosed and guarded stations	Enhanced vehicles with CCTV	Few special measures
Security	Low level of segregation	High level of segregation	Low level of segregation	High level of segregation
Image	Use of branding elements But: low visibility (infrastructures)	Use of branding elements High visibility (infrastructures)	Clean vehicle technology Use of branding elements	High visibility (infrastructures) But: no branding elements
Cust. care	Largely independent of BRT class			
Env. impact	Standard propulsion technology No special infrastructure	Standard propulsion Heavy infrastructure	Modern vehicle and propulsion technology	Standard propulsion Heavy infrastructure

4.5 Capacity – the operator's perspective

A common understanding of the capacity of a transport system is the maximum number of vehicles, spaces, or persons that can be moved past a fixed point in one direction, usually per hour (Vuchic, 2005, p. 624). Capacity is important to operators mainly out of efficiency considerations. To meet the efficiency goal of transporting passengers at a minimal cost (Weidmann, 2008, p. 51), the capacity offered by a public transport system needs to be somewhere close to the demand. Since many urban public transport systems are (sometimes heavily) subsidised through the public budget, the quest for public transport systems with a good match between demanded and supplied capacity is also a concern of the community. This chapter addresses the question of capacity of different BRT types and analyses the situations in which the capacity limits of BRT systems are reached.

4.5.1 Capacity and influencing factors

To analyse the capacity of public transport systems, the two aspects of person and vehicle capacity have to be distinguished. Person capacity is defined as the maximum number of people that can be carried past a given location during a given time period under specific operating conditions, without unreasonable delay, hazard, or restriction, and with reasonable certainty (Kittelson & Associates Inc. et al., 2003, p. 1-16). Vehicle capacity is defined as the maximum number of vehicles that can pass a given location during a given time period (Kittelson & Associates Inc. et al., 2003, p. 1-17). Vuchic (2005, p. 93 - 98) lists typical capacity figures of different transport modes, even though local conditions cause the capacity of transport systems to vary greatly in practice, even within the same transport mode.

Factors influencing capacity

There is abundant literature on the subject of the capacity of transport systems. However, it is not always straightforward to indicate the factors influencing system capacity, or to calculate the maximum capacity of a system. Detailed listings of factors influencing capacity and procedures to calculate system capacity in public transport can be found in Vuchic (2005, p. 78 - 98) and Kittelson & Associates Inc. et al. (2003, p. 4-i to 7-68). The first author lists the following elements as being relevant to person capacity: vehicle dimensions, minimum headway, maximum offered line capacity (i.e. vehicle capacity of a corridor), and operating speed. The latter authors list the following factors: vehicle characteristics, ROW level, stop (i.e. station) characteristics, operating characteristics (e.g. schedule layover time requirements at the final stops of a line), passenger traffic characteristics (ridership peaking and passenger distribution at stops), street traffic characteristics, and method of headway control (signalling technique). Both listings clearly unveil the particular importance public transport priority and ROW on capacity. Kittelson & Associates Inc. et al. list the ROW level explicitly as a determinant factor of system capacity. The listing by Vuchic implicitly includes the ROW level in minimum headway, maximum line capacity, and operating speed. Hence, a higher level of ROW does not only improve the quality of service delivered to the user, but also the capacity of a system. Additionally, higher levels of ROW can lead to improvements in cost-efficiency, as it will be shown later in this work.

BRT elements and capacity

Diaz et al. (2009, p. e-5) analyse BRT system elements for their influence on system capacity. They identify the following elements as being relevant to capacity: running way location, level of PT priority, station location and type, curb design, platform layout, passing capability, vehicle configuration, passenger circulation enhancement, fare collection process, payment options, fare structure, vehicle prioritisation, intelligent vehicle systems, operations management systems, and frequency of service. This listing means that six of the seven previously identified BRT dimensions (all except for branding elements) influence the system capacity. This fact again illustrates that the elements of the BRT concept are not only focused at improving the quality of service, but to a large extent also capacity. Grava (2003) discusses the capacity of conventional bus operation in mixed traffic (p. 339) and of BRT operation on segregated running ways (p. 416). He concludes that the key to a high capacity in mixed traffic is to maintain a steady and constant headway. He identifies the ability of the busiest stop to process vehicles and passengers as a critical element and indicates that the theoretical maximum capacity in mixed traffic is around 9000 passengers per hour per direction. In contrast, he concludes that an hourly capacity of 15,000 riders per hour per direction can be approached if a “whole array of BRT concepts and devices” is employed. He considers especially segregated busways and off-line stops with passing capability as important elements to increase capacity.

4.5.2 BRT systems reaching capacity

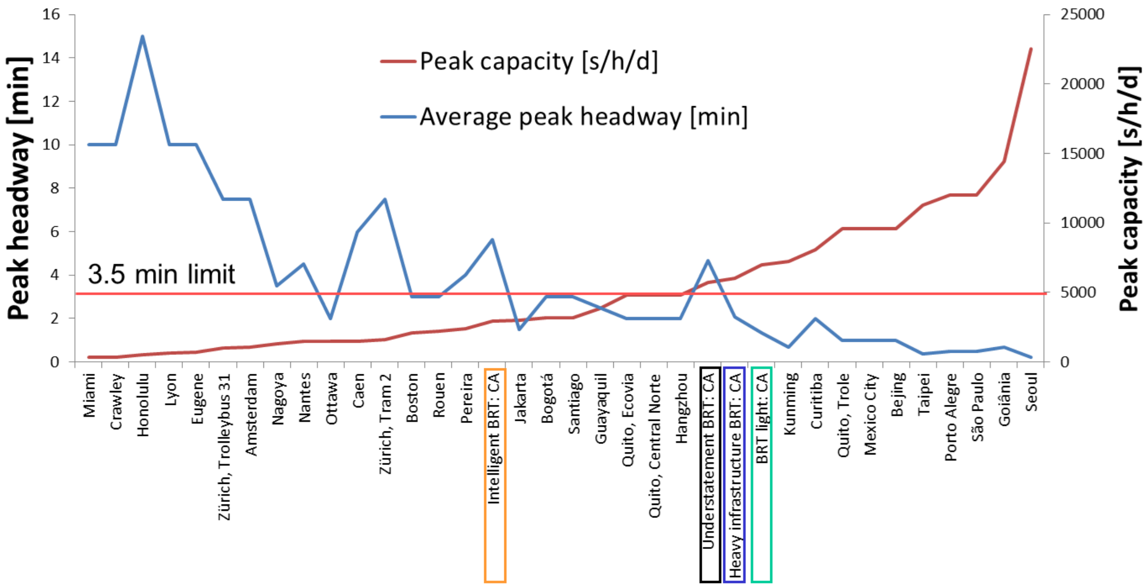
Diaz et al. (2009, p. e-6) state that in virtually all BRT systems implemented in the United States, capacity has not been an issue. They remark that in all systems, there is still leeway to expand capacity by using larger vehicles, operate at higher frequencies, or both. They add that in Latin American and Asian BRT systems, higher amounts of passengers are transported at fast commercial speeds and with a high reliability. The above statement does not imply that

BRT systems that do not reach their capacity are inefficient. Rather, the systems operate in a variety of urban settings, and are not always targeted at delivering a maximum throughput. In practice, the capacity of a public transport system will often not be exploited completely. There are many systems where services do not operate at the highest possible frequency, even during peak hours. Sometimes, limitations in available resources (vehicles, drivers, financial resources, etc.) hinder the provision of the maximum possible frequency and capacity. But in most cases, the passenger demand is simply not sufficient to justify operation at the capacity limit (Kittelson & Associates Inc. et al., 2003, p. 1-17). Additionally, an operation at the capacity limit might not be favourable with regard to other performance elements, especially regarding the quality of service. Vuchic (2005, p. 87 - 89) highlights the importance of the conditions under which the capacity is achieved. These conditions include operating speed, comfort standards, reliability, and the load factor. He indicates that a high capacity is often traded off against lowering the comfort standard, or against tolerating that due to overcrowding, not all passengers may be able to board the first vehicle that passes their station. Additionally, reliability and commercial speed decrease with an increasing frequency of service and shorter headways (Vuchic, 2005, p. 95). As mentioned before, Bruun (2005, p. 20) locates a critical headway threshold at about 3.5 minutes, below which a satisfactory level of reliability becomes difficult to maintain.

Capacity figures and limits of BRT systems

Figure 15 lists peak headway and capacity figures of existing BRT systems. Firstly, it can be noted that most systems provide a peak capacity of up to about 10,000 spaces per hour per direction (s/h/d), and there are a few systems providing higher capacities. Secondly, there is no system providing a capacity above ca. 3000 s/h/d with an average headway above 3.5 minutes. Accordingly, an approximate capacity limit of BRT systems up to which a satisfactory reliability is reached could be located at 3000 s/h/d. It could even be stated that an operation with headways of 3.5 minutes and a capacity of around 3000 s/h/d is an optimum in terms of reliability and capacity. Systems operating close to this optimum are Bogotá (Colombia) and Santiago (Chile). Interestingly, the cluster averages of understatement BRT, heavy infrastructure BRT, and BRT light are close together in terms of peak capacity. The cluster average of intelligent BRT systems shows a lower peak capacity of this BRT class and a longer average headway between services. This coincides with the above findings that intelligent BRT systems are not primarily focused at providing the highest possible capacity but rather at delivering a high quality of service level.

Figure 15 Peak headway and capacity of BRT systems



CA = Cluster average. s/h/d = spaces/hour/direction. Data sources: Diaz et al. (2009), Wright et al. (2007), Nationmaster.com (2011).

The figure also shows that many systems offer a capacity above 3000 s/h/d. The extreme case of Seoul (South Korea) with an offered capacity of 22,500 s/h/d will be discussed in the next section. Vuchic (2005, p. 95) states that in practice, it has proven possible to operate bus services at a very high frequency with an acceptable quality LOS if the city has policies favouring public transport. To illustrate this finding, Figure 20 later in this work will show that some BRT examples still offer a high commercial speed in spite of extremely short headways.

The absolute upper capacity threshold

Figure 15 showed that the understatement BRT system of Seoul (South Korea) offers a very high peak capacity of ca. 22,500 s/h/d. This figure originates from Wright et al. (2007, p. 776), where it is indicated that peak frequency in the Seoul BRT corridor is 4-5 buses per minute. The off-peak frequency still amounts to 3-4 buses per minute. Interestingly, the high capacity is not even achieved by using articulated or bi-articulated high-capacity vehicles, but by using conventional standard buses with a length of 10-12 metres and a capacity of 75 passengers. Apart from the theoretical capacity figure, the above authors indicate an observed peak ridership of 12’000 passengers/hour/direction in the Seoul BRT system. This means that on average, each standard bus is occupied by about 40 passengers during peak hours. During off-peak hours, when ridership is 5’000 passengers/hour/direction, this figure declines to about 23 passengers per bus. To achieve such short headways, massive infrastructures are required. Figure 16 gives an impression of the infrastructures that enable the BRT system in Seoul to achieve peak headways of only about 20 seconds. It becomes clear that the construction of the space-consuming infrastructures of this type might not be possible in all urban contexts.

Figure 16 The BRT system in Seoul has extremely short headways, offers a very high capacity, and consumes a large amount of space

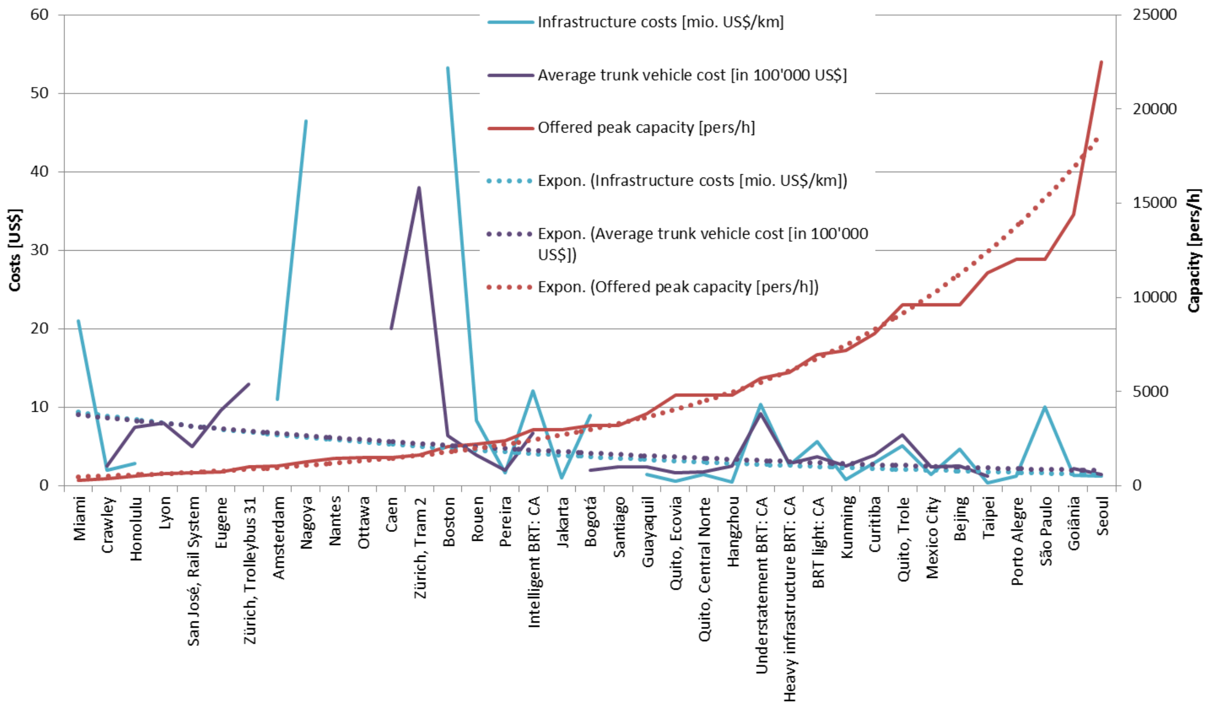
Image source: Kim (2010)

An example where the highest theoretically possible throughput of a bus service can be observed in practice is the exclusive bus lane in the Lincoln tunnel in New Jersey (USA). Grava (2003, p. 416) states that on this lane, up to 730 buses per hour have been observed, which implies a headway of only 4.9 seconds. If each bus carries 50 passengers, Grava indicates the achievable throughput to 36,500 riders per hour. Apart from this extreme figure, Grava locates a reasonable upper threshold for the capacity of BRT systems at about 14,000 riders per hour. He comments that this limit could only be achieved by using off-line stops with passing facilities, skip-stop services, and few signal interruptions (i.e. segregated running ways or vehicle prioritisation). Vuchic (2005, p. 95) identifies the theoretically possible upper capacity thresholds of bus lines at about 90-120 vehicles/h in mixed traffic, whereas the upper limit can only be achieved if stations allow for a simultaneous passenger exchange of more than one vehicle. If bus convoys, bi-articulated buses, four-lane stations, and other capacity-increasing measures are introduced, he states that a maximum throughput of 300 buses per hour could be achieved, offering a capacity of up to 30,000 spaces per hour per direction. These figures, however, only provide an insight into the theoretically possible upper capacity thresholds of bus systems and do not take into consideration if such an operation pattern is reasonable from a quality or cost point of view.

Higher investments are not always targeted at yielding more capacity

Figure 17 compares the capacity of existing BRT systems to infrastructure and vehicle costs.

Figure 17 Offered peak capacity and capital costs of BRT systems



CA = Cluster average. Data sources: Diaz et al. (2009), Wright et al. (2007).

Figure 17 illustrates that all outlying cost values occur in systems with a comparably low capacity, to the left side of the figure. In contrast, all systems to the right side of the figure have a high capacity and comparably low infrastructure and vehicle costs. The interpolated regression line is somewhat distorted by the outlying cost values on the left side, but there still seems to be a weak negative correlation between costs and capacity. This leads to the conclusion that the highest investments in systems are rarely a result of measures to increase capacity, but rather caused by special circumstances, such as the construction of bus tunnels in the case of Boston or the acquisition of expensive vehicles in Caen.

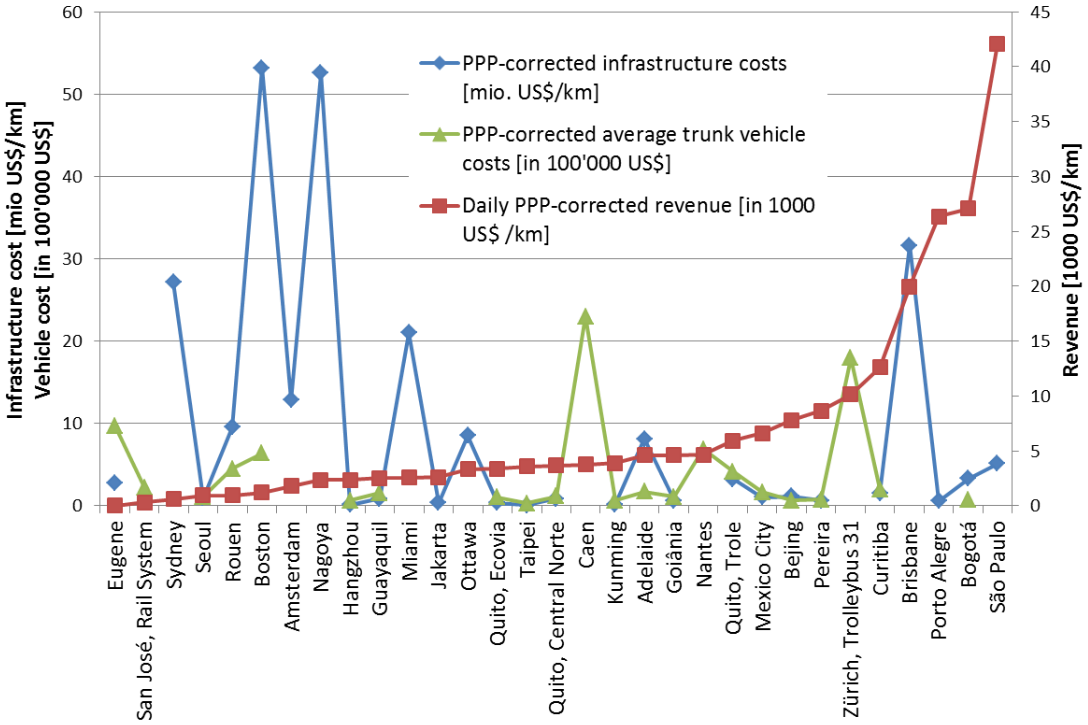
4.6 Cost-efficiency – the community's perspective

The community is another actor who is interested in the performance of public transport systems. As presented in chapter 4.1, the interests of the community encompass amongst others the passenger attraction, costs, social objectives, environmental impact, and energy consumption. These interests are guided by underlying sustainability goals, such as promoting an economically, ecologically, and socially viable urban environment. The economical aspect is important since not only the construction, but mostly also the operation of public transport systems is sometimes heavily subsidised by the community. Therefore, the community is interested in public transport systems that allow a great degree of cost-efficiency. Since efficiency in general terms is the amount of output that can be generated with a certain amount of input (Weidmann, 2009, p. 9), the community is interested in a system that generates a maximum of output by consuming a minimum of input. For public transport, this means that a (quantitative and qualitative) maximum of passenger trips should be produced for a minimum of input. Broadly defined, input includes not only the public subsidies, but also the negative impacts on the community (noise, pollution, severance, etc.). This efficiency task is met differently by different transport modes, since they have individual performance characteristics. For example, heavy rail can produce a high number of transported passengers at a potentially high quality, but at a comparably high cost. In contrast, a conventional bus system is only able to transport a fraction of the passengers at a lower quality level, but requires less input than a heavy rail. Therefore, the optimal range of application of transport modes in terms of cost-efficiency depends largely on the demand in the individual case.

4.6.1 BRT costs and benefits

The costs and benefits of BRT systems can be assessed by using the method of cost-benefit analysis. Echeverry et al. (2005) provide an example of a cost-benefit analysis for the TransMilenio BRT in Bogotá (Colombia). They compare revenue, operational costs, and monetised costs from increased waiting, access, and egress time, as well as monetised benefits from reduced travel time, reduced air pollution, and mortality. It would go beyond the scope of this work to perform a thorough cost-benefit analysis of BRT systems, but the previously used data on fares and daily ridership can be used to compare daily revenue of BRT systems to capital costs. Figure 18 illustrates that the systems with the highest PPP-corrected daily revenue per kilometre are the examples of São Paulo, Bogotá, Porto Alegre, Brisbane, and Curitiba. These cities appear to have fixed the fares at a level that allows for a high financial sustainability of the system and avoids heavy subsidies by the public budget. The systems of Eugene, Sydney, Rouen, Boston, Amsterdam and Nagoya generate high capital costs and little revenue. Accordingly, these systems are likely to require subsidies by the public budget. The system of San José is a special case since only a limited service during peak hours is provided. Therefore, comparably few passengers are transported and the daily revenue is low. Especially the systems of Seoul, Hangzhou, Jakarta, Quito, Taipei and Kunming show a combination of low revenue and also quite low capital costs.

Figure 18 Revenue and system costs



Data sources: Diaz et al. (2009), Wright et al. (2007), Nationmaster.com (2011).

In this analysis, daily revenue was calculated by multiplying the number of daily passengers with the fare. This calculated revenue is therefore only an approximate figure, since travelcards and other discounts are not considered, even though in some cases, significant numbers of passengers are using them. Since the systems are very different in size, daily revenue was not calculated in absolute figures, but standardised for one kilometre of system length. Because the purchasing power of generated revenue varies considerably between countries, it was additionally rectified with the purchasing power parity correction factor.

4.6.2 Other objectives by the community

As mentioned above, cost-efficiency is not the only interest of the community. Sustainability goals in an economical, ecological, and social sense are often mentioned as a concern of the community. Grava (2003, p. 5 - 6) identifies more specific goals of the community and divides them into communal and national concerns. For example, he highlights the importance of efficient networks supporting economic and social life, efficient urban patterns, a high degree of liveability, fiscal affordability, institutional peace, civic image, and political approval. In fact, political approval is an extremely important success factor in the implementation of BRT systems. Hidalgo (2010a, p. 23) identifies the launches of the second phase of TransMilenio in Bogotá (Colombia), and Transantiago in Santiago (Chile) as cases where insufficient public information and an accordingly low political approval led to chaotic conditions in the introduction phase. Avoiding such incidents is also a key concern by the community.

4.7 Chapter review

In this chapter, the performance of BRT systems has been addressed regarding quality of service, capacity, and cost-efficiency. The valuation of performance differs between users, operators, and the community and individual perceptions play a role. Quality of service is the overall measured or perceived performance of transit service from the passenger's point of view, in terms of availability, accessibility, travel time, reliability, user cost, comfort, safety, security, image, customer care, and environmental impact. Possibilities to influence the performance of a transport system have been detected at the planning and operation stages of new systems. It is not always possible to define an optimal level of service (LOS) and service providers should strike a balance between quality and affordable services. The LOS has an influence on ridership and customer satisfaction. It is not straightforward to identify the elements of a service that actually define its quality. In the case of BRT, especially the dimensions of running ways, stations, vehicles, and intelligent transport systems considerably influence the quality that is delivered to customers. One of the most important underlying factors is the level of public transport priority and right of way (ROW) since it directly affects travel time, reliability, comfort, safety, and environmental impact. Increasing the ROW also reduces operating costs by reducing the required fleet and manpower. In urban transport, frequency is a very important quality element whereas lower comfort levels (e.g. load factors) are tolerated. This chapter also provided a detailed evaluation of the quality of service of BRT systems. Findings indicate that BRT systems allow for quality improvements in comparison to conventional bus operation mainly in terms of capacity, accessibility, comfort, safety, and image.

Capacity evaluations unveiled that especially in Latin American and Asian BRT systems, high numbers of passengers are transported. However, the systems are not always targeted at delivering a maximum throughput. In many cases, demand does not justify an operation at the capacity limit. Especially the class of intelligent BRT systems is not primarily focused at providing the highest possible capacity but rather at delivering a high quality of service. The capacity of systems can be increased by a further segregation from other traffic, by using larger vehicles, by operating at higher frequencies, or by lowering the comfort standard. However, reliability and commercial speed decrease with an increasing frequency of service. A critical headway threshold for maintaining a sufficient reliability has been located at about 3.5 minutes. Accordingly, an approximate capacity limit of BRT systems up to which a satisfactory reliability is reached could be located at 3000 spaces per hour per direction (s/h/d). The maximum capacity of bus systems in mixed traffic has been indicated to around 9000 passengers per hour per direction. By increasing the segregation from other traffic, by using larger vehicles and stops with passing facilities, a reasonable upper threshold for the capacity of BRT systems could be located at about 14,000 s/h/d. The provision of such a high capacity requires very high frequencies of service and massive infrastructures.

5 BRT and beyond: comparing modes

In many cities, BRT has become a popular alternative to rail-based systems since it allegedly offers the possibility of combining relatively low construction costs with favourable performance characteristics. However, the planning and implementation of rail-based systems in cities around the world has not come to a halt. On the contrary, rail-based systems are still being constructed in various locations and prove to be a valid choice for situations in which the capacity and quality limits of BRT systems are reached and where systems with a higher performance are desired. On the other hand, it is not always necessary to increase capacity and there are numerous cities where the level of public transport ridership is low. In these cases of low demand, a costly upgrade from conventional bus services to BRT may not be justified. The choice of a transport mode in the individual case depends on the specific local requirements regarding capacity and quality, and on the financial possibilities of a community. The choice of a transport system is influenced by local factors and conditions, such as the salary, material, and energy cost levels, by spatial limitations of the urban environment, and by local preferences regarding design, safety, and comfort. The specific social and environmental impacts of public transport modes also influence the choice of transport systems (based on Wright et al., 2007, p. 1). The local circumstances and preferences vary considerably, and it will not be possible to define general threshold values for the choice between modes that apply to all cases. Nevertheless, the limitations of BRT systems can be identified and explored in general terms, especially regarding quality and capacity. Whereas there is abundant literature on BRT planning and implementation, less research has been done on the subjects of the limitations of the BRT mode regarding capacity and quality of service. Some authors even state that the drawbacks and limitations of BRT systems are topics typically avoided by BRT promoters (for example Light Rail Now Project Team, 2009). According to some authors, the inclusion of quality aspects into mode comparisons has become more popular in recent years, while hypothetical and mainly cost based mode comparisons have become less common (for example Vuchic, 2005, p. 525).

Chapter outline: this chapter aims at identifying the factors influencing the choice between transport modes and at comparing systems accordingly. Since a main argument of BRT advocates is the allegedly low cost of this mode, the financial aspect will be discussed at first, and critique to monetary comparisons will be presented. Subsequently, a parametric cost model will be used to analyse the influence of labour cost levels, commercial speed, material and energy costs, unit capacity, and minimum frequency requirements on the performance of modes. The different BRT classes that have been identified earlier in this work will be compared to conventional bus and light rail transit (LRT) operation to identify threshold levels of mode choice and the ranges in which either mode might be superior to others. Additional criteria for the decision between transport modes will be discussed subsequently, such as further quality aspects, the ability to create networks, city size, implementation time, and passenger attraction. The mode comparisons in this chapter are mainly based on the average values of the previously identified BRT classes. Mode comparisons that are based on specific system examples have been performed by Vuchic (2005, p. 547-549), comparing BRT and LRT operation in the USA. Echeverry et al. (2005, p. 180) compare the costs and benefits of conventional bus and BRT operation in the case of Bogotá (Colombia).

5.1 System alternatives to BRT

5.1.1 Conventional bus

Conventional bus operation as an urban public transport system normally does not cause great excitement. In many cases, common buses do not offer particularly comfortable service and tend to get caught in traffic, leading to slow and unreliable service. Their operation is relatively labour-intensive since capacity per vehicle is limited in comparison to other public transport modes (section based on Grava, 2003). This poor operational performance and inadequate customer service lead to a long-standing negative stigma and a low public image of conventional bus services. Wright et al. (2007, p. 20) even state that in cases of low quality bus operation, “public transport” often brings with it the same connotation of unpleasantness as “public toilets”. Nevertheless, conventional bus operation has important advantages above other public transport modes. It is readily implementable and flexible in operations and in meeting all kinds of demand conditions. Conventional bus systems offer lower investment costs than other public transport modes since technology is readily available and standardised, and no special workforce is required (Grava, 2003, p. 381). More comfortable, accessible, and cleaner vehicles, as well as improvements in speed and reliability will contribute to improve this mode, leading it to the edge of BRT operation. In absolute numbers, buses have been an unprecedented success story in public transport. Figures from all over the world show that the advantages of conventional buses have clearly outweighed their drawbacks. Buses are the “workhorses of the transport world” and their dominance is evident in passengers carried, vehicle kilometres travelled, size of fleet, workers employed, etc. (section based on Grava, 2003, p. 301-302).

5.1.2 Tram and light rail transit (LRT)

Trams usually operate in mixed traffic or on separated lanes in city streets and usually have short station spacing (Grava, 2003, p. 809). Light rail transit (LRT) is a rail-based urban public transport mode operating mostly with exclusive rights-of-way at ground level, on aerial structures, in subways, or occasionally in streets (based on Kittelson & Associates Inc. et al., 2003, p. 8-47). Vuchic (2005, p. 89) shows that in comparison to conventional trams, a modern LRT system offers advantages in speed, reliability, comfort, and capacity. In comparison to BRT systems, LRT offers an even greater comfort, image, and land development benefits, whereas it implies higher investment costs and longer implementation times (Vuchic, 2005, p. 591). LRT offers particular advantages in capacity and labour productivity if medium to high numbers of passengers are to be transported. It also improves reliability and safety of operations, quality and attractiveness of ride, energy efficiency and environmental friendliness, as well as image and community acceptance of public transport. Reasons to exert caution are its lower flexibility and its potentially higher construction and maintenance costs in comparison to bus-based modes, and a higher level of interference with street traffic in comparison to heavy rail systems (section based on Grava, 2003, p. 466-471).

5.2 Money matters: financial comparisons

One main argument of BRT advocates are the allegedly lower implementation costs in comparison to rail-based transport systems. Wright et al. (2007, p. 11) claim that BRT essentially emulates the performance and amenity characteristics of a modern rail-based transit system but at a fraction of the cost. They state that a BRT system will typically cost 4 to 20 times less than a light rail transit (LRT) system and 10 to 100 times less than a metro system. If this statement is true, the question remains of why LRT and metro systems are still being built at all. In any case, there are several aspects in the statement which can be debated. Firstly, the above figures only address capital costs for constructing a system and exclude operating costs. The inclusion of operating costs is important because they vary greatly with the supply and demand characteristics, such as the required frequency of a service or the number of passengers having to be transported in a corridor within a certain time. Secondly, the previous chapters of this work have shown that the quality and capacity characteristics vary considerably between modes and even between BRT classes. Accordingly, it would be a very rough approximation to consider BRT and LRT to be close to equal in terms of performance and amenity characteristics. This chapter will examine how useful such financial comparisons really are in identifying possibilities and limits of different modes. It can be anticipated that there are good reasons to exert caution when comparing systems on the base of costs and when stating that one system is superior to another because it simply is cheaper. A step beyond financial comparisons will be made in chapter 5.3. There, quality criteria will be included into the mode comparisons and the factors influencing cost-capacity thresholds between modes will be analysed in detail.

5.2.1 Money matters - or does it? Critique of financial comparisons

Approaches that compare different modes mainly in terms of costs are severely criticised by Vuchic (2005, p.522 - 525). This author states that several theoretical economic studies have been performed for hypothetical urban corridors, utilizing average costs from different cities, or with some assumed values. He argues that these studies have been repeated with the same conceptual and methodological errors, leading to the frequent conclusion of favouring lower-cost modes while overlooking quality of service and capacity characteristics of apparently more expensive modes. Vuchic concludes that it is incorrect to only regard the criterion of minimum costs per passenger trip, since the difference in quality between a more expensive transport mode and a more economical one may well be worth its additional costs. In addition, he states that these studies often ignore externalities of transport modes, and face difficulties in including mode characteristics that cannot be easily converted into monetary units, such as comfort, image, reliability, and others. Moreover, these studies often disregard the inherent potential of different transport modes to attract passengers (i.e. the previously discussed rail bonus). Vuchic highlights that the break-even point between modes is a fictitious concept because the curves in a coordinate system between passenger volume and cost per person-trip are on different LOS surfaces in terms of quality of service, and hence do not intersect. Vuchic argues that the results of these theoretical analyses that often favour the "cheapest" mode have often been used by interest groups to argue against improvements of public transport infrastructure, particularly of rail transit. Despite all this critique, Vuchic approves that these financial comparisons can still give some indication of the optimal domains of different transport modes when properly performed and interpreted with care. It can be concluded that a purely financial comparison, such as the above example by Wright et al. (2007, p. 11), does not provide sufficient information for a decision on the optimal transport mode, since it largely excludes capacity and quality considerations. The following chapters therefore aim at extending the comparison from a cost-based approach to including other dimensions of performance. However, the inclusion of further dimensions into the evaluation complicates the issue of finding general threshold values between different modes. This illustrates the need for including thorough analysis of relevant factors, such as the developments in demand and labour cost levels, as well as in the public budget and in local preferences.

5.2.2 Comparing capital costs

The exact capital costs of a system depend on local factors, such as the labour cost level, local physical conditions, financing costs, design and safety requirements, etc. (Wright et al., 2007, p. 54 - 55). These authors indicate typical infrastructure capital costs per kilometre to be between 500,000 and 15 million US$ for BRT systems, with most systems being delivered for under 5 million US$ per km. The costs for at-grade tram or LRT systems are indicated to 13 to 40 million US$ per km. Underground metro systems range from 45 to 350 million US$ per km. Vuchic (2005, p. 525) argues that these capital cost comparisons often confuse technologies with modes. He states that the infrastructure costs of modes mostly depend on the ROW category and not on the choice between bus and rail technology. He points out that an exclusive busway infrastructure may involve higher investment and operating costs than light rail transit operating in the street median. Bruun (2005, p. 20 - 21) analyses the effects of including costs for vehicle purchase and overhauls. Even though he considers BRT vehicle costs of ca. 0.5 million US$ and LRT vehicle costs of ca. 2 million US$, he concludes that the annual cost impact is about the same for BRT and LRT since he assumes LRT vehicles to benefit from a longer life cycle. The cost impact can even be higher for BRT if specialised and expensive vehicles are used, such as it is the case in some intelligent BRT systems.

5.3 Beyond money: comparing costs, capacity and quality

As demonstrated in the previous chapters, purely financial comparisons do not provide a sufficiently complete picture of the advantages, disadvantages, and optimal ranges of application of modes. Hence, this chapter expands the scope of mode comparisons and includes capacity and quality considerations. This chapter will provide quantitative analysis of different factors affecting the capacity, costs, and quality of transport systems. The influencing factors can be divided into system-specific characteristics of modes and external factors. Examples of system-specific characteristics are the vehicle capacity and system speed, with all the subordinate factors influencing speed, such as station spacing, the level of ROW, vehicle prioritisation, the alignment of running ways, vehicle and station characteristics, fare collection, propulsion technology, user education and so on. External factors influencing system performance (for example in terms of system costs) are the labour cost level, maintenance costs, price levels for fuel, energy, tires, lube, expendables, etc., as well as political determinations such as minimum frequency requirements. With the help of model calculations, approximate threshold levels for the choice between different transport modes will be explored for different model conditions. A parametric cost model for transport modes developed by Bruun (2005) will be used to simulate different scenarios to analyse the performance levels and thresholds for different transport modes when influencing factors and circumstances are changed. Mostly, the differences between modes do not only incur in terms of costs, but also in terms of quality. Hence, the final choice of an optimal transport mode should be guided by case-specific valuations of these changes in quality. The topic of monetary valuation of quality characteristics is not included into this analysis and presents an ample area of further research.

5.3.1 A parametric cost model for mode comparison

Bruun (2005) developed a parametric cost model to provide average and marginal operating cost estimates for conventional bus, light rail transit (LRT) and bus rapid transit (BRT) operation in a model network. The model uses data from the U.S. National Transit Database and allows a comparison of annual operating costs for LRT and BRT operation under given circumstances. In his study, Bruun uses data from the Dallas Area Rapid Transit agency in Texas, USA, as an example of a medium sized transport agency with representative and contemporary performance statistics for both the LRT and the bus mode.

Costs incurred per hour, kilometre and year

For the purpose of calculating the total annual operating costs of different modes in a model network, Bruun first provides formulae for calculating the unit costs per vehicle-hour, vehicle-kilometre, and vehicle-year. He then calculates the costs incurred in the specific case of Dallas as a basis. This differentiation in unit costs per hour, kilometre, and year accounts for the fact that some costs in reality incur per hour of operation, whereas others are more related to kilometres travelled. Especially the staff costs (i.e. the operator, supervisory, and other staff wages and prorated fringe benefits) are in reality related to the hours of operation of a vehicle, whereas maintenance and propulsion costs incur per kilometre travelled. In more practical words, drivers get paid per hour and not per kilometre travelled, but the consumption of fuel or electricity is determined primarily by the travelled distance and not by the hours of operation. There are additional costs which are neither related to the hours of operation, nor to the number of travelled kilometres. These costs include nonvehicle maintenance costs for the upkeep of all fixed facilities, such as offices, depots, and route infrastructure, as well as management, planning, legal department, accounting, insurance and other costs resulting from the general administration of the transport operator. For simplicity reasons, these costs for keeping one unit available for one year are set to be proportional to the fleet size in the following simulations and are held constant at the level that Bruun found for the case of Dallas, USA.

The model equations of cost components

In the following equations, the cost components are differentiated in costs per hour, per kilometre and fix yearly costs. The costs incurring for one bus-hour of operation are labelled C_{BH}, for one bus-kilometre C_{BK}, and for keeping one bus available for transport operation during one year C_{FS}. The last cost component is neither related to operating hours nor to kilometres travelled. The calculation of LRT operating costs follows the same pattern. Bruun studies a LRT system where trains can be adapted in length and capacity by being composed of one, two, or three consists (i.e. railcars). The unit costs of operating a three-car train are of course not equal to the triple costs of operating a one-car train, since (for example) both trains require only one driver, disregarding of how many cars are coupled to it. Thus, there are cost components, such as the driver's salary, which are independent of the number of railcars in a train. Other costs, such as the costs for propulsion (in a rough approximation) incur for each railcar separately. Accordingly, the cost component C_{TH} incurs for one train-hour of operation, whereas C_{CK} and C_{FS} incur for each railcar-kilometre or railcar-year separately. The components that constitute unit costs incurred per bus or train hour and per bus or railcar kilometre are listed in the following. The monetary values that Bruun found for the case of Dallas are also indicated.

$$C_{BH} = \frac{staff\ costs}{revenue\ bus{-}hours} = 39.95\ \text{US\$/h}$$

$$C_{TH} = \frac{staff\ costs}{revenue\ train{-}hours} = 93.27\ \text{US\$/h}$$

$$C_{BK} = \frac{vehicle\ maintenance\ cost + fuel, lube, tires \&other}{revenue\ bus{-}kilometres} = 1.53\ \text{US\$/km}$$

$$C_{CK} = \frac{vehicle\ maintenance\ cost + propulsion\ power + expendables\ specific\ to\ the\ rail\ mode}{revenue\ railcar{-}kilometres}$$
$$= 2.06\ \text{US\$/km}$$

The fixed figure C_{FS} annually incurs for nonvehicle maintenance and general administration. In the Dallas example, this figure accounts to 132'000 US$/year in the case of buses and to 362'600 US$/year in the case of railcars.

Calculating annual operating costs

As soon as the unit costs are known, total yearly operating costs can be calculated with the help of operation figures and statistics, such as yearly vehicles-hours, vehicle-kilometres, and fleet size. The yearly operating costs for standard bus and single-car train operation are calculated with the following equations:

$$AC_{standard\ bus} = C_{BH}(yearly\ bus - hours) + C_{BK}(yearly\ bus - kilometres) + C_{FS}(fleet\ size)$$

$$AC_{single-car\ train} = C_{TH}(yearly\ train - hours) + C_{CK}(yearly\ railcar - kilometres) + C_{FS}(fleet\ size)$$

The total annual costs for operating one vehicle can be calculated if the fleet size is set to be one. By changing the above cost parameters, different scenarios for annual operating costs can be calculated when the yearly unit-hours, unit-kilometres, and fleet size are held constant. Under the assumptions that the system is running 18 hours per day on 365 days per year and at an average speed of 30 km/h, and using the figures form Dallas, the cost for operating one standard bus (fleet size 1) is 696’000 $. The annual cost of operating one single-car train is 1’381’400 $/year. In Bruun’s study, the average speed for buses is set to only 20 km/h, which reduces the number of travelled bus-kilometres per year. This, again, lowers the second component of $AC_{standard\ bus}$ and thereby reduces operating costs to 593’500 $/year. Of course, annual costs must be seen in relation to the offered capacity by a mode. In the case of Dallas, Bruun specifies the capacity of conventional 12 m-buses to 80 passengers (52 standing, 28 seated). The capacity per railcar with a length of 28 m is indicated to 186 (120 standing, 66 seated). Hence, a triple-railcar train offers a maximum capacity of 558 spaces.

Correction factors for articulated buses

Because the U.S. National Transit Database lacks entries for the operating costs of articulated buses or specialized BRT vehicles, Bruun uses crude correction factors to account for higher operating costs of articulated buses in comparison to standard vehicles. He suggests 1.2 as a lower and 1.4 as a higher estimation for a correction factor. This order of magnitude is supported by the findings of Weidmann (2008, p. 93), where correction factors for bi-articulated buses are suggested as well. Bruun states that a cost factor of 1.5 or greater would make articulated buses pointless from a cost point of view, because the cost per space-kilometre then equals or exceeds that of standard buses. For simplicity reasons, this crude approach to calculate costs of BRT vehicles is maintained in the modelling in this work and assumptions about the correction factor are stated in the individual case.

5.3.2 Bruun's findings for a model network – and some extensions

Bruun in his study applies the above numbers to a model network. He considers the case of a medium-sized metropolitan area with a diameter of 32.2 km (20 miles). The transport system is designed to consist of radial trunk corridors with a length of 16.1 km, which are served by a 15 minutes headway base service. A minimum additional layover and recovery time of 15% is defined for the change of direction and breaks for the driver in both ends. In a first approximation, the operating speed is set to be 30 km/h on the trunk corridors, independent of whether LRT, conventional bus, or BRT operation is considered. The base service fleet requirement is determined by the following equation:

$$N = \left[\frac{2L_{Trunk}}{velocity * frequency}(1 + 0.15)\right]^{+}$$

With the above specifications, the base service fleet requirement to operate the system in the model network is 5 units. The resulting line capacities and operating costs for running this base service with different transport modes are summarised in Table 11. BY this means, it becomes clear that a mere comparison of operating costs does not provide a sufficient basis for a decision on transport modes, since line capacity is very different in each case. In addition, quality components which are influenced by mode-specific characteristics, such as comfort, safety, image, and accessibility are yet to be included into the analysis.

Table 11 Line capacities and operating costs for different modes in a model network

	Single railcar LRT	Conventional bus	Articulated bus, lower cost correction factor (1.2)	Articulated bus, higher cost correction factor (1.4)
Vehicle capacity [spaces]	186	80	120	120
Line capacity [s/h/d]	744	320	480	480
Annual operating costs [million US$]	6.9	3.48	4.18	4.87

BRT is superior to LRT if overall demand is low

An interesting finding by Bruun is that for approximately the same cost of operating a single railcar train service every 15 minutes, the operator could afford to operate a fleet of 7-8 articulated buses, leading to a service running about every 10 minutes. This would provide roughly the same capacity as the LRT service (i.e. 778 spaces per hour per direction), but offer a higher quality of service in terms of availability, since the service is running at a higher frequency. Hence, in the case that a capacity of about 770 spaces per hour per direction (s/h/d) is sufficient, Bruun concludes that the headway-versus-cost trade-off favours articulated buses. In a second scenario, where the speed of conventional bus services on the same corridor is set to only 20 km/h, he concludes that both articulated bus and LRT operation running at 30 km/h have lower operating costs on a per kilometre basis than do conventional buses. He identifies the separated ROW characteristics – and thus higher revenue speeds – of the first two modes, in combination with the use of larger vehicles, as the driving forces behind this cost advantage. In any case, the higher per unit operating costs in the case of LRT become less of a disadvantage as soon as demand increases. Bruun states that above a demand of about 2000 s/h/d, single-railcar LRT provides increasingly attractive frequencies of 10 min or less at lower cost than BRT. In addition, longer three-railcar LRT trains can provide a capacity of 2232 spaces per hour at 15-min headways, whereas a similar capacity requirement would imply 3.5-min headways for the case of BRT, which Bruun considers problematic. He states that headways below 3.5 minutes make signal priority difficult and mostly reduce revenue speed. This increases the required fleet number and hence also the operating costs. Because such short headways imply a danger for delay propagation and irregular service, the potentially high (temporal) availability of the service is in this case traded off against a lower quality of service regarding travel time and reliability.

LRT is superior to BRT if off-peak demand is high

Bruun also provides detailed calculations for the case that some services are only added in peak hours or when additional consists (or railcars) are added to trains in peak hours. He concludes that the ability of trains to carry more cars during peak periods while still needing only one driver more pronouncedly lowers the cost for adding peak capacity in the LRT case than in the BRT example. More importantly, the cost saving for adding capacity during the times between the peaks very much favours LRT, since the costs of adding an extra railcar to a train during off-peak periods is only 0.011 US$ per space-kilometre, whereas the corresponding figure for operating additional BRT vehicles between the peak hours is 0.038 US$ per space-kilometre. Thus, Bruun concludes that LRT has a clear advantage in cases where off-peak demand is expected to increase over years. The low cost for offering extra capacity during off-peak hours in the case of LRT may also be used as an argument for leaving the extra cars coupled to the train during the entire day, if the costs for coupling, shunting and handling of extra railcars equal or exceed the potential savings from lower costs because less kilometres are travelled per railcar. Another interesting general finding in Bruun's study is that the return on investment may be much higher from investing in improving efficiency of tangential routes instead of further improvements to the trunk lines, once they are in place. This is because the costs for providing universal coverage through a dense tangential network are far higher than the costs of operating the trunk line network.

5.3.3 Operating costs of BRT and LRT at an equal operating speed

In this chapter, the parametric cost model developed by Bruun will be used to evaluate the performance of the four BRT classes that have been identified in chapter 3. Subsequently, their performance will be compared to LRT operation. To generate average values of vehicle capacity and system speed for each BRT class, the empirical data of the systems analysed in chapter 3 have been considered again here. The four BRT classes and the calculated average values of unit capacity and system speed are summarised in Table 12.

Table 12 Unit capacity, vehicle type and operating speed of BRT classes

	BRT light	**Heavy infrastructure BRT**	**Understatement BRT**	**Intelligent BRT**
Average unit capacity[9]	120	162	84	118
Typical vehicle type	Articulated bus	Bi-articulated or articulated bus	Standard bus	Articulated bus
Average operating speed [km/h]	19.25	20	22.5	29.3

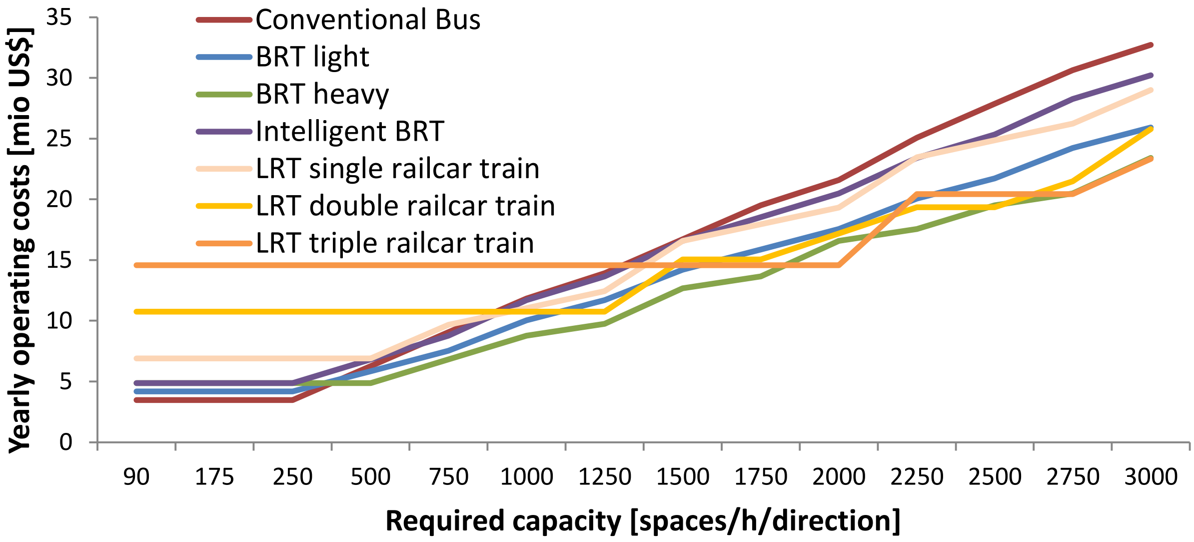
In a first attempt to compare the performance of BRT classes, only the average vehicle capacity is considered, whereas operating speed is set to 30 km/h for all classes. The class of understatement BRT is excluded from the following analyses, since it shows almost the same unit capacity and operating speed as conventional bus operation. For simplicity reasons, the scenarios that are developed in the following assume the operating fleet size to be constant over the entire day. Detailed procedures for the calculation of scenarios in which the service fleet is extended only during peak hours can be found in Bruun (2005, p. 14-19).

Which mode meets a fixed demand at minimal costs?

A comparison of the cost-capacity characteristics of the four BRT classes and the LRT mode where all modes have the same operating speed of 30 km/h is displayed in Figure 19.

[9] Average values from the system examples presented in chapter 3, excluding the data from San José and Zürich (rail systems).

Figure 19 Yearly operating costs of BRT and LRT modes with equal operating speeds for fixed capacity requirements



In contrast to Bruun's approach, the comparison does not depart from a pre-defined uniform headway requirement for all modes, which results in different capacities since unit capacity varies strongly between modes. In fact, this analysis considers the performance of modes in meeting previously fixed capacity requirements. Hence, the approach used in this work focuses at the question of which system can meet a given capacity requirement in a corridor at a minimal operating cost, and not which capacity is achieved by different systems operating at the same frequency. The model constraints in this case are the following:

1. All model cost parameters from Bruun's findings for the case of Dallas, Texas, are used unchanged here. This first approximation is therefore a picture of situations with an USA cost level.
2. A corridor of 16.1 km length is to be served by different modes. In this first approximation, all modes are set to have an identical average operating speed of 30 km/h.
3. The required capacity is set to be equal during the entire day of operation (18 hours on 365 days/year).
4. The unit capacities from Table 12 are used for the BRT classes, whereas the capacity of one LRT railcar is 186 passengers, as in Bruun's study.
5. Operating costs of BRT modes are set to be 1.2 times the cost of conventional buses in the case of BRT light to account for the use of articulated vehicles. This factor is 1.4 for heavy BRT, to account for the use of bi-articulated vehicles. It is also set to 1.4 for

intelligent BRT, to account for the cost of articulated vehicles and the higher cost for a more widespread use of intelligent transport systems.

6. A maximum headway (i.e. a minimum frequency) of 15 minutes is required in the model for quality reasons. Bruun (2005, p. 11-12) argues that this headway is a common policy maximum for urban base services. Without this maximum headway requirement, the result of the model would be that the LRT mode satisfies a low demand with a train every 60 minutes, causing very low operating costs. Even though this is theoretically true, temporal availability would be greatly inferior to a more frequent bus service, and patronage would decline sharply. However, there are cities where urban transport systems with a relatively low frequency and a high capacity are implemented, such as in the example of the San José suburban rail system. This pattern of service is often found in suburban services, where speed and comfort are weighted higher than frequency compared to urban public transport services.

In Figure 19, the yearly operating costs are lowest for conventional bus (or understatement BRT) operation up to a required capacity (i.e. demand) of between 250 and 300 spaces per hour per direction. Between roughly 500 and 2000 s/h/d, the heavy infrastructure BRT class has the lowest operating costs. With the above assumption of an equal speed in all modes, intelligent BRT is not able to compete with heavy BRT due to the lower unit at an equal per unit cost (because the same correction factor is applied). Single LRT railcar trains with roughly the same capacity as bi-articulated buses but at a higher per unit cost are equally inferior to BRT modes in terms of yearly costs, if an equal operating speed is assumed. However, the operation of triple railcar trains becomes an alternative for required capacities above ca. 2000 s/h/d, where the yearly operating costs of this mode become equal or inferior to heavy BRT.

Cost-capacity curves are on different quality LOS surfaces

As stated in chapter 5.2.2, caution in these comparisons is needed since modes cannot simply be compared in terms of operating costs, because they do not provide an equal quality of service. In the words of Vuchic (2005, p. 525), the curves between demand and costs are on different LOS surfaces for each mode and do not intersect. Therefore, the choice between modes should not only rely on the break-even point in operating costs, but even more on valuations of the different quality characteristics of modes. Rail-based systems usually provide a higher riding comfort, have a higher impact on land use development, and generate more ridership. Therefore, a LRT system might be considered a better alternative even at a lower demand than the threshold level in terms of operating costs indicates. For example in the case of 1250 required s/h/d, the operating costs between BRT heavy and double railcar LRT trains are quite close to each other and the cost – quality trade-off could be considered to favour LRT operation. A second major difference in quality, or more precisely in temporal availability, occurs in terms of the headway between services. Table 13 shows that triple railcar LRT trains are able to meet a demand of 2000 s/h/d with 15 minutes headway between services. In contrast, the operation of heavy BRT with articulated buses would require a maximum headway of 4.6 minutes to provide for the same capacity for only slightly higher operating costs. Hence, heavy BRT operation might in this case be considered the favourable alternative, since it allows for a much more attractive frequency for users than does an LRT system.

Table 13 Maximum headway [min] of systems to meet demand

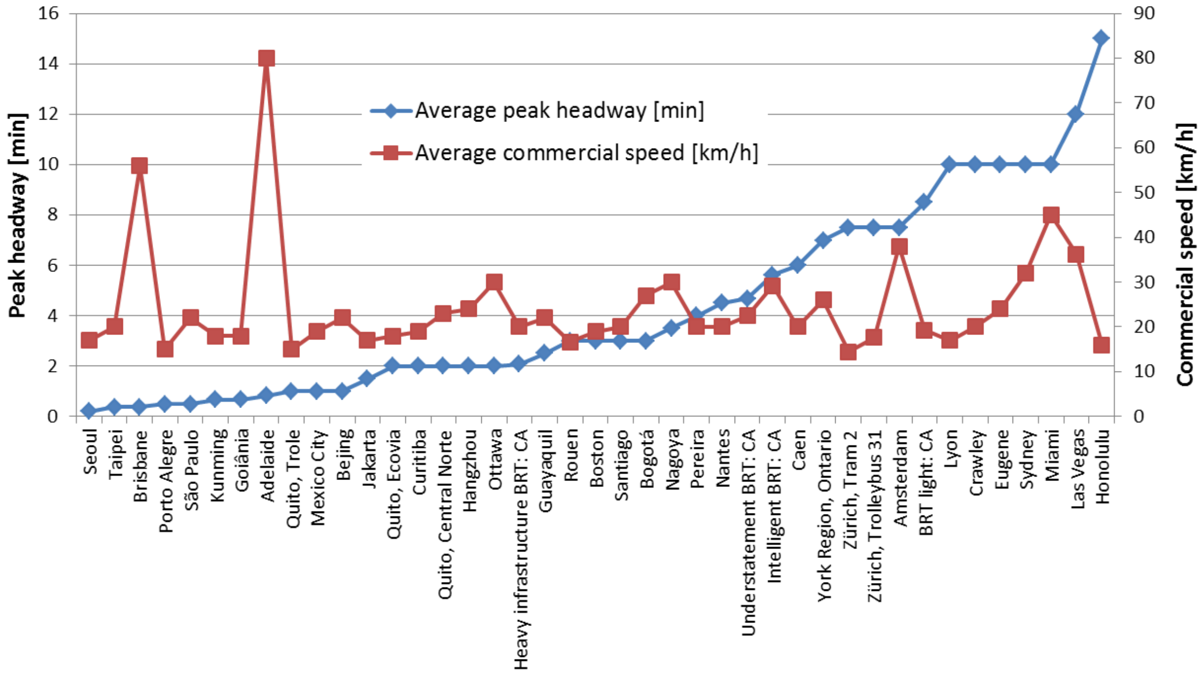
Demand [s/h/d]	Conven-tional bus	BRT light	BRT heavy	Intelligent BRT	LRT single railcar train	LRT double railcar train	LRT triple railcar train
90	15.0	15.0	15.0	15.0	15.0	15.0	15.0
175	15.0	15.0	15.0	15.0	15.0	15.0	15.0
250	15.0	15.0	15.0	15.0	15.0	15.0	15.0
500	8.6	12.0	15.0	12.0	15.0	15.0	15.0
750	6.0	8.6	12.0	8.6	12.0	15.0	15.0
1000	4.6	6.7	8.6	6.7	10.0	15.0	15.0
1250	3.8	5.5	7.5	5.5	8.6	15.0	15.0
1500	3.2	4.6	6.0	4.6	6.7	12.0	15.0
1750	2.7	4.0	5.5	4.0	6.0	12.0	15.0
2000	2.4	3.5	4.6	3.5	5.5	10.0	15.0
2250	2.1	3.2	4.3	3.2	4.6	8.6	12.0
2500	1.9	2.9	3.8	2.9	4.3	8.6	12.0
2750	1.7	2.6	3.5	2.6	4.0	7.5	12.0
3000	1.6	2.4	3.2	2.4	3.5	6.7	10.0

Headway limitations for high demand levels

A second important finding from Table 13 is that for a demand above ca. 1500 s/h/d, headway for conventional bus operation drop below the level of 3 to 4 minutes. Bruun (2005, p. 20) states headways below 3 to 4 minutes can be problematic in and a high commercial speed becomes difficult to maintain. He adds that the assessment of whether or not the commercial speed can be maintained at such short headways can only be done by a project specific simulation. To illustrate the limitations of bus and BRT modes regarding too short headways, the problematic headways of less than 3.5 minutes are highlighted with a red colour in Table 13. Figure 20 shows that in practice, BRT systems with headways shorter than 3.5 minutes are very common. Surprisingly, the highest operating speeds are found in the cases of Brisbane and Adelaide, with extremely short headways. This finding can be partly explained by the large station spacing in these systems of between 1.5 and 5 kilometres. In addition, these two

Australian understatement BRT systems are radically separated from other traffic. The system of Adelaide even features laterally guided vehicles that allow very high travel speeds above 80 km/h on the busways with mechanical guidance

Figure 20 Peak headway and commercial speed of existing systems



In most cases, the short headways do not allow average commercial speeds greatly exceeding 20 km/h. It could also be suspected that average commercial speed is a figure that is measured throughout the whole day and the values in Figure 20 do not provide a good representation of the commercial speed during peak hours since the speed can probably not be maintained during peak hours in the cases where peak headway is very low. It is more probable that systems with short headways, such as Seoul and Taipei, tend to get so crowded with buses in peak hours that commercial speed and reliability declines sharply during these times.

Quality considerations

Table 14 provides an example of the differences in the quality of service. The table summarises the performance of heavy infrastructure BRT, single-railcar LRT trains, and triple-railcar LRT trains in terms of the quality criteria where differences incur most notably. These include availability, travel time, reliability, and comfort, even though differences in accessibility, user cost, safety, security, image, customer care, and environmental impact may also incur.

Table 14 Quality differences between BRT heavy and LRT

		Transport mode		
		Heavy infrastructure BRT	Short LRT trains	Long LRT trains
Quality criteria	Availability	Temporal availability very good, very frequent services: below 6 min headway above 1500 s/h/d	Temporal availability very good, very frequent services: Below 6 min headway above 1750 s/h/d	Temporal availability reduced: 15 min headway for 2000 s/h/d, 10 min headway for 3000 s/h/d
	Travel time	Reduced: commercial speed of only 20 km/h	Good: commercial speed of 30 km/h	
	Reliability	Reasonable up to 2750 s/h/d	Reasonable up to 3000 s/h/d	Reasonable up to far more than 3000 s/h/d
	Comfort	Reduced smoothness of motion: street running vehicles	Increased smoothness of motion: rail-based technology	

5.3.4 Commercial speed and operating costs

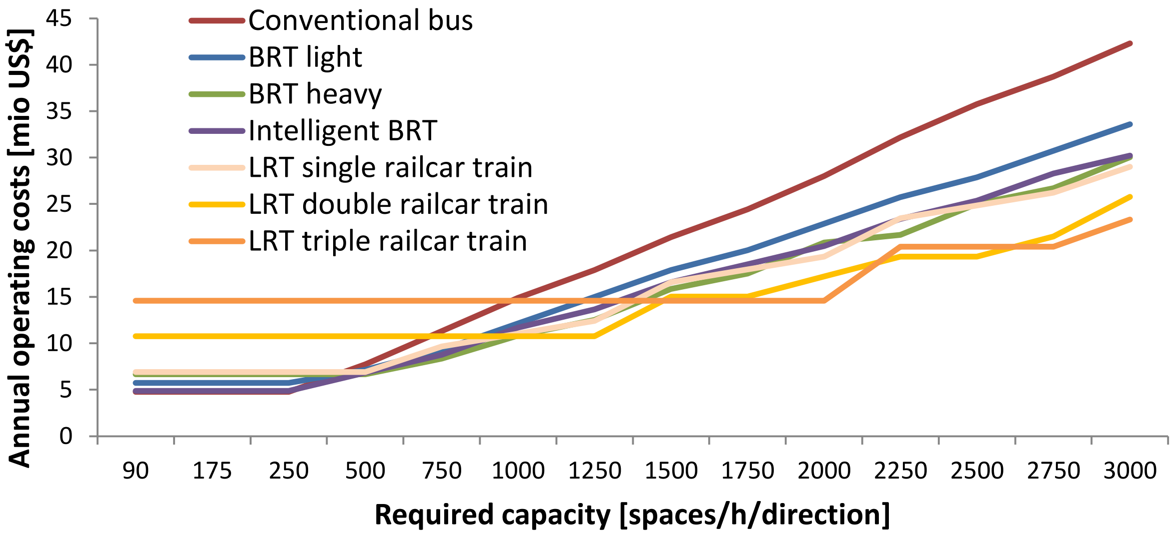
So far, the analysis has considered a scenario where all BRT and LRT systems are set to have equal commercial speeds (also named operating speeds) of 30 km/h. However, Table 12 showed that this is not the case in practice. Only the class of intelligent BRT systems achieves an average operating speed close to 30 km/h, whereas the average operating speed of other BRT classes is around 20 km/h. This difference is mainly explained by the higher average station spacing (see Figure 9) and the widespread use of intelligent transport systems for vehicle prioritisation in the intelligent BRT class. To include these differences in operating speed, the above analysis will be repeated in this chapter, with the operating speed of BRT light, BRT heavy and conventional bus set to 20 km/h, whereas intelligent BRT and LRT have operating speeds of 30 km/h.

Cost implications of commercial speed

According to Bruun's model, yearly per unit costs decline with a lower operating speed. This is because a lower operating speed means less kilometres travelled per unit and year (when the hours of operation remain equal) and thus to a lower consumption of the cost components related to kilometres travelled (such as maintenance costs, fuel, tires, etc.). On the other hand, more vehicles are required to maintain the same frequency of service. For example in the case of conventional bus operation, 5 vehicles are needed to provide a service with 15 minutes headway in the above model network corridor, if an operating speed of 30 km/h is assumed.

In contrast, 8 units are needed if the operating speed is lowered to 20 km/h. The result of including the mode specific operating speeds, when all other cost factors are held at the initial USA cost level, is summarised in Figure 21.

Figure 21 Yearly operating costs of BRT & LRT modes with specific operating speeds for fixed capacity requirements



These results show the great influence of operating speeds. In contrast to Figure 19, where intelligent BRT showed higher operating costs than other modes in all cases, this class now becomes a valid choice for a demand of up to about 1000 s/h/d, if its higher operating speed in comparison to other BRT classes is considered. If demand is 250 s/h/d or less, conventional bus operation has a slight cost advantage above intelligent BRT. Its annual operating costs are 4.77 million US$ against 4.87 million US$ in the case of intelligent BRT. But the higher operating speed of intelligent BRT means a higher performance from the user's point of view, since speed is an important quality criterion. Both conventional bus and intelligent BRT systems can meet a demand of up to 250 s/h/d with services every 15 minutes, so there is no difference in temporal availability in this case. Reliability and customer information might be better for intelligent BRT, since the use of ITS technology allows for a better management of irregularities and service disruptions. Therefore, the acceleration of conventional bus systems or the change to intelligent BRT might be considered even at low demand levels since there are benefits in operating costs to the operator and in quality to the users. White (2002, p. 59) describes the case of Leeds (UK), where the acceleration of a conventional bus system led to an increase in commercial speed and thus to a reduction of operating costs. The quality improvement was also perceived and honoured by users, resulting in substantially higher patronage. After these improvements, the system was labelled as a BRT system and appears in the understatement BRT category of this work. In the medium range of a demand between 500 and 1000 s/h/d, the advantages of the higher capacity of bi-articulated heavy BRT vehicles offsets the disadvantage of the lower operating speed of this class in comparison to intelligent BRT. In this range, slower heavy BRT systems can compete with faster intelligent BRT systems in terms of capacity and operating costs. However, intelligent BRT offer a more frequent service at the same cost. To satisfy a demand of 750 s/h/d, intelligent BRT needs to provide a service with 8.6 minutes headway, whereas heavy BRT systems with larger vehicles need to provide service only every 12 minutes at almost equal costs. Above 1000 s/h/d, rail-based modes have clear cost advantages above all BRT modes due to their higher commercial speed and vehicle capacity.

BRT is more competitive at higher speeds

In a next step, scenarios are analysed where travel speed is not a mode-specific figure but a variable parameter. This accounts for the fact that in reality, system speed varies largely within the same mode or BRT class. For example, within the class of heavy infrastructure BRT, the trolleybus BRT in Quito (Ecuador) has an average commercial speed of only 15 km/h, whereas the TransMilenio system in Bogotá (Colombia) reaches an average commercial speed of 27 km/h, i.e. almost the double. To account for these differences, Figure 23 compares different scenarios of commercial speed, ranging from 10 to 35 km/h. Since intelligent BRT and triple railcar trains proved to be the most valid candidates for different demand levels in the above analysis, only these two modes are compared in this illustration. The fact that commercial speed has a great influence on the operating costs in both modes is indicated by the skewness of both cost surfaces from the front to the back of the diagram, i.e. from high to low commercial speeds. In both modes, an increase in commercial speed contributes a great deal to the reduction of annual operating costs and to the competitiveness of the mode. For example, if both modes are supposed to meet a demand of 2000 s/h/d and operate at a speed of 35 km/h, LRT operation is superior in terms of costs. If for some reason, the commercial speed of LRT is only 10 km/h while the speed of intelligent BRT remains at 35 km/h, the picture changes. If the annual operating cost point of intelligent BRT at a speed of 35 km/h is projected to the back of the three-dimensional diagram (represented by the red line), it ends up well below the cost of LRT operation. The difference in annual operating costs is represented by the dotted red line. It indicates that in the case of these different operating speeds, intelligent BRT would clearly be the superior choice in terms of operating costs. Interestingly, the graphs in Figure 22 indicate as well that the threshold between intelligent BRT and triple railcar LRT train operation changes also if commercial speed is varied equally for both modes. If both modes have a very low operating speed of 10 km/h, the cost – capacity equilibrium point between intelligent BRT and LRT is just around a demand of 1500 s/h/d. This threshold of 1500 s/h/d is represented by the green line indicating the position of the equilibrium point when transferred onto the demand axis. In the case that both systems have high commercial speeds, intelligent BRT is able to compete up to a demand of around 1600 s/h/d, represented by the purple line. This difference may not be very large, but it indicates that bus-based modes are actually more competitive to rail-based modes if the speed of both modes is increased by the same amount.

Figure 22 Commercial speed scenarios and thresholds between intelligent BRT and LRT

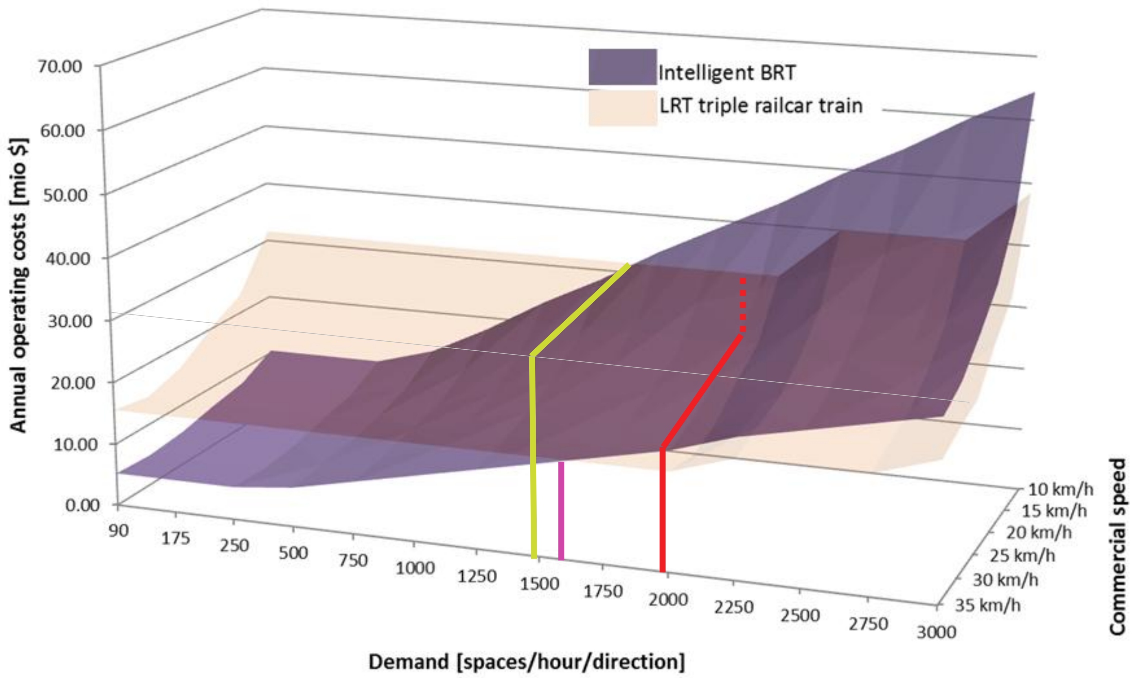
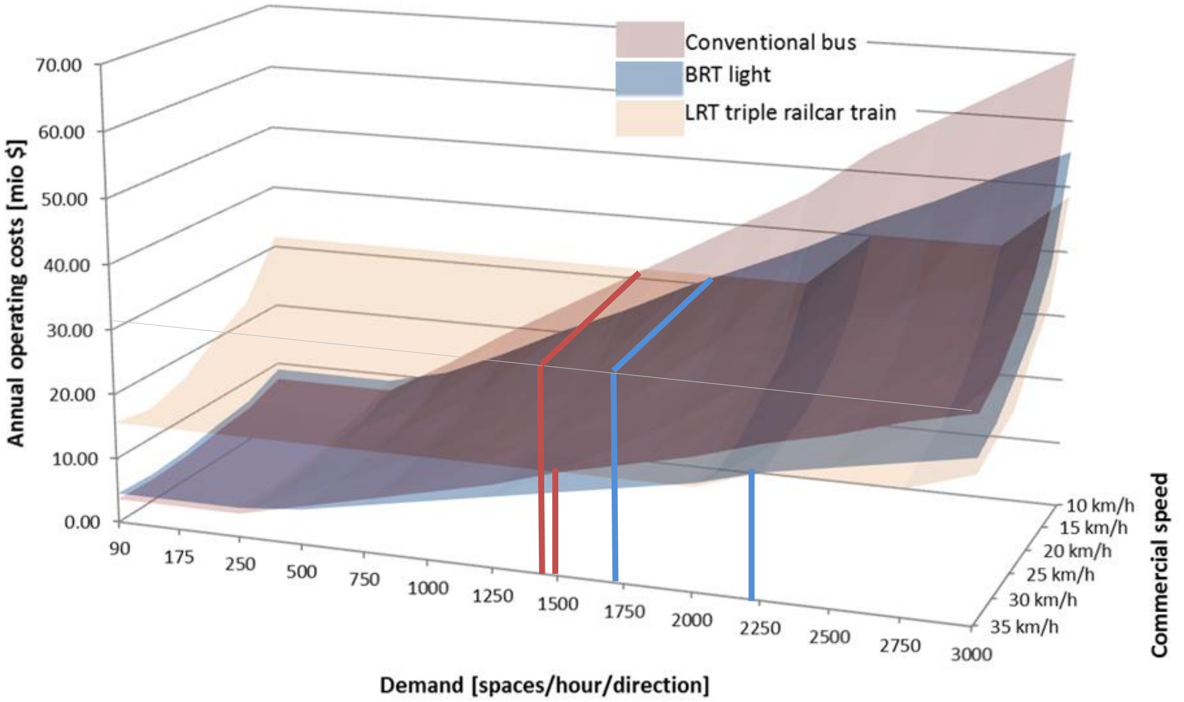


Figure 23 illustrates that this phenomenon occurs even more pronouncedly when comparing conventional bus, BRT light, and LRT operation. In the case of conventional bus operation, the break-even point in operating costs with triple railcar LRT trains is located at a demand of around 1500 s/h/d, disregarding the shared commercial speed level (represented by the two red lines). In contrast, the demand threshold between BRT light and LRT varies substantially for different levels of commercial speed. This is represented by the two blue lines indicating thresholds at demand levels of 1750 and 2250 s/h/d. The same pattern as in the above case of intelligent BRT operation is observed here, since the threshold is at a substantially higher demand level when both systems have a higher commercial speed. This observation indicates that speed improvements in bus operation contribute even more in the reduction of annual operating costs than they do in the case of rail-based modes.

Figure 23 Commercial speed scenarios and thresholds between conventional bus, BRT light, and LRT



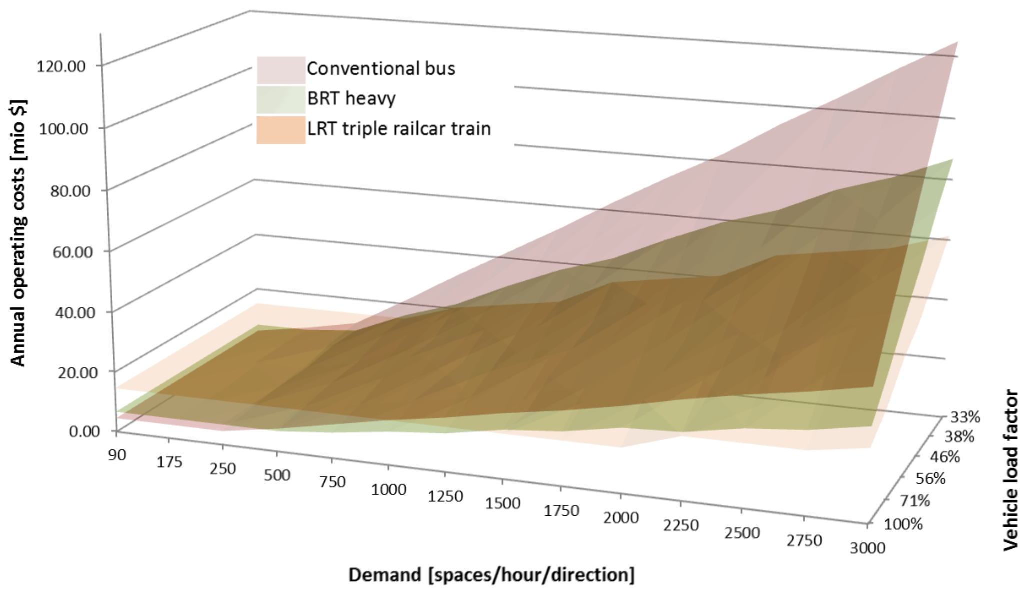
The importance of commercial speed

The above findings again highlight the crucial importance of commercial speed in terms of quality of service, capacity, and operating costs. The factors influencing the commercial speed of a system have already been discussed in chapter 4.4. It was stated above that on average, intelligent BRT systems with a high level of vehicle prioritisation provide substantially higher commercial speeds than heavy infrastructure BRT systems that rely mostly on segregated running ways. This makes it clear that segregation alone is not a sufficient measure to increase commercial speed. However, if station spacing is increased and station dwell time is reduced to a minimum, a higher ROW category contributes much to achieving higher operating speeds. This requires consistent public transport prioritisation and a radical elimination of interference with other traffic. Because of the important influence of commercial speed on operating costs, measures to move systems to a higher ROW category may be well worth their costs. The fact that increasing commercial speed reduces operating costs again confirms the statement that both users, operators and the community (at least if a system is subsidised by the public budget) benefit from increases in commercial speed.

5.3.5 Quality requirements and operating costs: the vehicle load factor

The above calculations considered scenarios without restrictions for the occupancy of vehicles since the maximum allowed vehicle load factor was always 100%. This means that in the model, in the cases of rising demand, the offered capacity is only increased if vehicles are filled up to a 100% of their capacity. However, from a quality of service point of view, it might not be desirable to operate with a vehicle load factor of up to 100%, since overcrowding of vehicles implies a reduced (physical) availability, reliability, and commercial speed through longer station dwell times because passengers experience difficulties in boarding and alighting. Therefore, Figure 24 analyses different scenarios of maximum vehicle load factor restrictions. For example in a scenario with a vehicle load factor restriction of 71%, additional capacity has to be provided (by increasing the frequency of service) as soon as a vehicle is filled up to 71% of its capacity.

Figure 24 Annual operating costs depending on vehicle load factor



The most obvious finding from Figure 24 is that at a high demand level (e.g. at 3000 s/h/d), annual operating costs increase sharply with stricter vehicle load factor restrictions. However, in the case of low demand scenarios, the increase in operating costs is much lower, because vehicles operate at the minimum pre-defined frequency of every 15 minutes and are far from being filled up to capacity. A scenario with a maximum allowed vehicle load factor of 33% in all modes means that roughly all seats are occupied and no passengers are required to stand. So, in the hypothetical case that a transport operator defines a quality of service standard that all passengers find an available seat during the peak hour, and if demand is 3000 s/h/d, annual operating costs of all three displayed transport modes almost triple in comparison to a scenario without this quality of service standard. The cost-capacity equilibrium points between the modes are at considerably lower demand levels for strict load factor requirements (to the back of the diagram) and at higher demand levels if no load factor requirements are defined (to the front of the diagram). This indicates that bus modes are relatively more competitive compared to LRT if vehicles are allowed to fill up to capacity than if only a limited occupancy is tolerated.

5.3.6 Labour cost levels

The formulae in chapter 5.3.1 indicate that the cost structures vary considerably between bus, BRT, and LRT modes. In conventional bus operation, vehicle operation costs account for a large part of the annual costs, since the lower unit capacity implies that more drivers are required per passenger than in the case of BRT or LRT systems. In the case of LRT systems, the fixed cost per unit is higher, whereas fewer drivers are required to transport the same number of passengers than in the case of bus systems. Accordingly, the different modes show different reactions to changes in the labour cost (i.e. salary) level.

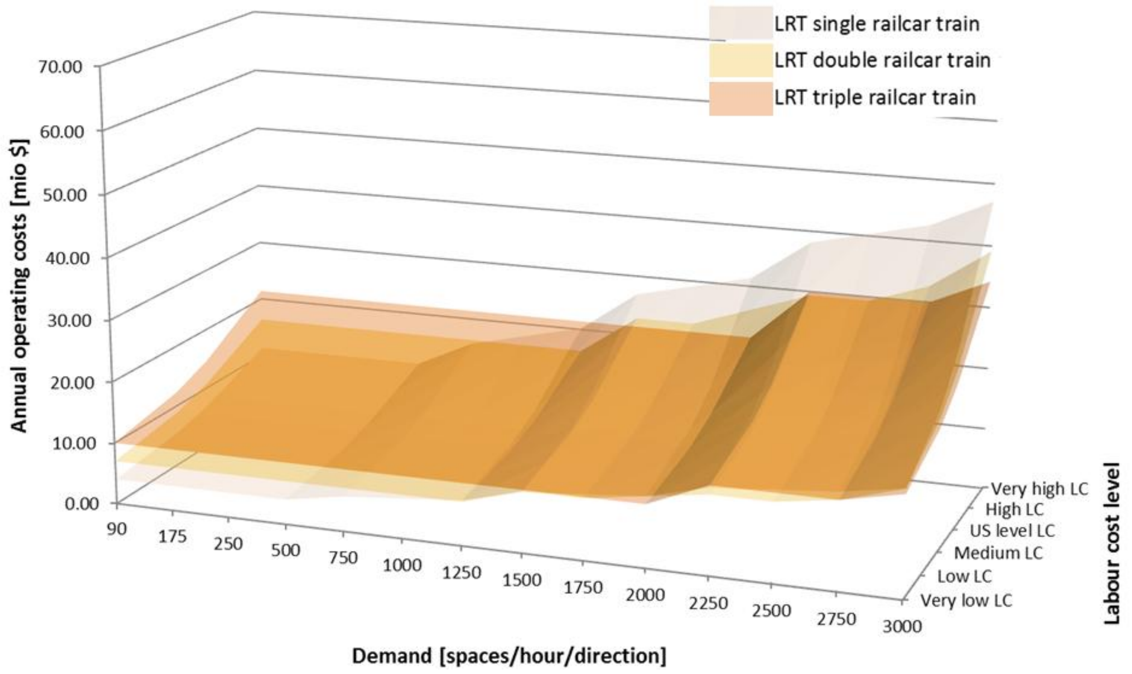
Labour cost scenarios

The following analysis will compare the cost-capacity surfaces of LRT, bus, and BRT for different wage level scenarios. The data from Bruun's study are used to create an initial scenario with US level labour costs. The maximum possible vehicle load factor is set to 100% for all cases, so vehicles are allowed to fill up to the capacity limit. The different scenarios are then calculated by changing the variables of vehicle operations costs (operator, supervisory and other staff wages, and prorated fringe benefits) and vehicle maintenance costs (labour for maintenance, expendables, and parts consumption & support vehicle costs). For the scenarios of very low, low, and medium labour costs, the US figures of these variables are respectively divided by 3, 2, and 1.5. The scenarios with high and very high labour costs are computed by multiplying the US figures respectively with 1.5 and 2. As in the above example, the differences in operating speeds between modes are maintained in this analysis to provide a more realistic cost comparison. Hence, conventional bus, BRT light, and heavy infrastructure BRT have a commercial speed of 20 km/h, whereas intelligent BRT and LRT have a commercial speed of 30 km/h.

Economies of scale in LRT operation

To provide a first insight into the effects of different labour cost levels on operating costs, the annual operating costs for different train lengths of the LRT mode are presented in Figure 25.

Figure 25 Annual LRT operating costs depending on train length and labour cost level

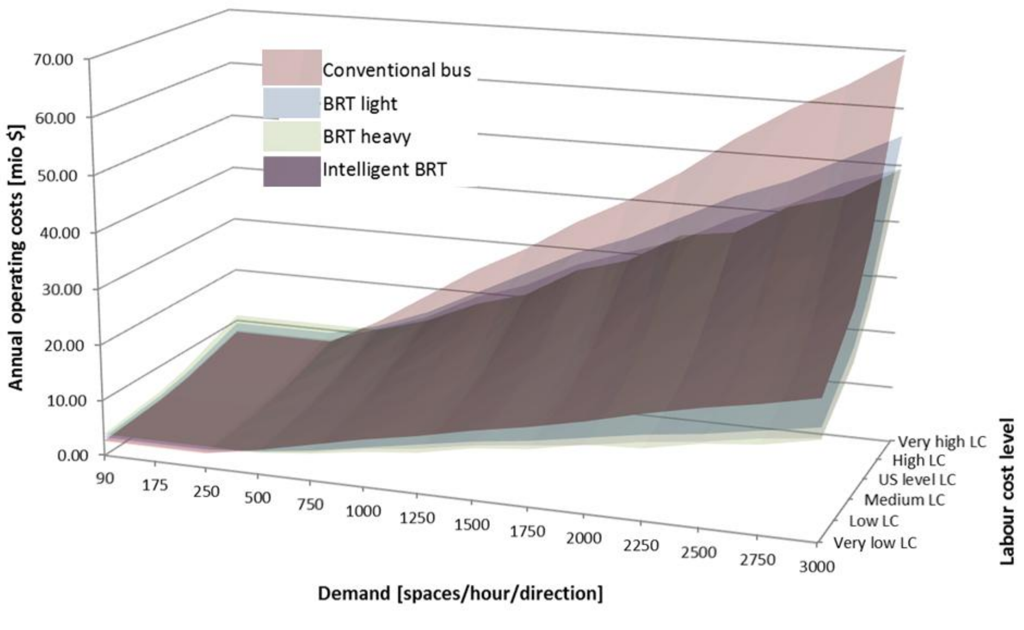


As expected, single railcar trains have the lowest cost per unit, and thus the lowest annual costs when operating at the same minimum frequency as longer trains for a low demand scenario. From a demand of about 1000 s/h/d, economies of scale make trains with two railcars more cost-efficient than single railcar trains. The same applies to trains of three consists from a demand of about 1500 s/h/d and higher. In the scenario of very low labour costs (US costs divided by 3, the front part of the cost surfaces), the operating cost surfaces remain almost at the same level for higher demand scenarios, disregarding the train length. Hence, the saving from operating longer trains is minimal if labour cost levels are low. On the contrary, there are quality reasons to favour shorter trains in this case. Namely, single railcar trains will need to operate at a higher frequency than longer trains to satisfy medium and high demands. In the case of a demand of 3000 s/h/d, single railcars need to operate every 3.5 minutes to satisfy the demand, whereas three-railcar trains operate with 10 minutes headway. If the labour costs are very low, both alternatives cause approximately the same costs. In total, a frequent service with short trains in this case clearly is the superior alternative compared to longer trains at a lower frequency. However, the picture changes drastically if the labour cost level is higher. Namely, if a very high level of labour costs and a high demand is assumed, the gains from operating longer trains are substantial. In the case of a very high labour cost level, three-railcar trains with a unit capacity of 558 s/h/d are able to meet a demand of 3000 s/h/d with a service every 10 minutes at a yearly operating cost of about 34 million US$. In contrast, single railcar trains with a unit capacity of 186 s/h/d need to operate every 3.5 minutes, which results in operating costs of 47 million US$ per year. Accordingly, the difference in frequency between a service every 3.5 and 10 minutes would cost 13 million US$ per year in the case of high labour costs. The decision of which train length is to be favoured is a question of the valuation of the improvement in frequency of service (and thus the quality aspect of temporal availability). This observation again illustrates the statement by Vuchic (2005, p. 525) that the cost-capacity curves in fact are on different quality LOS levels and do not intersect. In general, it can be stated that an improvement in the frequency of service becomes more costly with increasing labour cost levels. In other words, the economies of scale from operating longer trains are more substantial at higher labour cost levels.

Economies of scale in BRT operation

Figure 26 illustrates similar comparisons for the different BRT classes. First of all, it can be noted that all BRT classes are able to meet a demand of up to at least 250 s/h/d with the base service operating every 15 minutes.

Figure 26 Annual operating costs of BRT classes for different labour cost scenarios

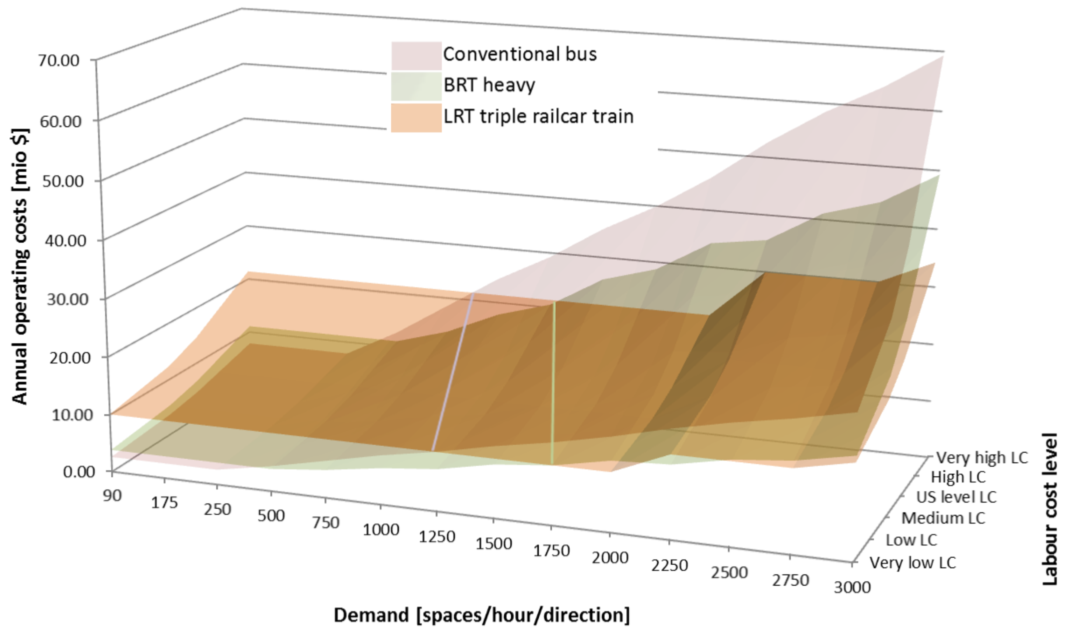


In providing the base service, conventional bus operation (and thus also understatement BRT) has a slight advantage in operating costs above all other BRT classes, disregarding the labour cost level. However, the implementation of BRT systems normally implies quality improvements in comparison to conventional bus operation, such as the accessibility advantages of enhanced vehicles and stations, or the travel time advantages because of a higher operating speed in the case of intelligent BRT. If the superior quality of service characteristics of BRT systems are considered to be worth the additional costs, the implementation of BRT systems might be a worthwhile alternative to conventional bus systems also in the case that only a basic service is provided. Not surprisingly, the cost advantage of conventional bus operation rapidly turns into a cost disadvantage for higher demand scenarios. Because of the low operating speed and the low unit capacity, the cost disadvantage of conventional bus service is even more pronounced in the case of high labour cost. The cost structure with a high share of staff costs per transported passenger turns into a clear disadvantage of this mode when labour costs rise. While the cost surface of the BRT light mode with a low operating speed and articulated vehicles with a higher capacity lies somewhere in the middle, the capacity advantage of the BRT heavy vehicles (bi-articulated buses) and the speed advantage of intelligent BRT systems lead to clearly lower operating costs in the case of high demand for these two classes, disregarding the labour cost level. In fact, faster intelligent BRT with articulated buses almost exactly parallels slower heavy BRT with bi-articulated buses in terms of cost-efficiency in the range between ca. 350 and 2000 s/h/d. Apart from the above cost considerations, it must be noted that not all BRT classes are able to meet the demand levels with a reasonable degree of reliability. If the previously discussed requirement of a minimum headway of 3.5 minutes (Bruun, 2005, p. 20) is not to be hurt, the maximum demand that a conventional bus system can meet is 1250 s/h/d. In the cases of BRT light, BRT heavy and intelligent BRT, the limits are around 2000, 2750, and 2000 s/h/d, respectively. Hence, heavy BRT is the only BRT system that is able to provide a capacity of up to 2750 s/h/d with a reasonable degree of reliability (i.e. with intervals above 3.5 minutes). Above this threshold, rail-based systems are the only alternative that can meet the demand with a reasonable degree of reliability.

Advantages of BRT at low labour cost levels

Figure 27 compares the annual operating costs of conventional bus, heavy BRT and triple railcar LRT trains regarding the above labour cost scenarios. The blue line crossing the cost surfaces indicates that the cost – capacity equilibrium between conventional bus and LRT is at a higher demand level for very low labour costs than it is in a high labour cost scenario. The same applies to the equilibrium point between heavy BRT and LRT, represented by the green line. The cost surface of triple railcar LRT shows a higher fixed cost for providing the base service. It intersects with the BRT heavy surface at about 1700 s/h/d for a very low labour cost level and at about 1250 s/h/d for a very high labour cost level. In the scenario of a very low labour cost level, the operating costs are close to equal between heavy BRT and LRT at a demand above ca. 1500 s/h/d. As a result, bus-based modes are more competitive to LRT operation if the labour cost level is low. This follows the different cost structures of the modes, since labour costs matter more in bus-based systems where more drivers are needed to transport the same number of passengers. This is an argument to implement BRT systems especially in countries with low labour cost levels. In these cases, BRT offers favourable cost conditions for substantially higher demand levels compared to countries with a high labour cost level. Inversely, it implies that LRT systems should be considered already at a lower demand in countries with high labour cost levels than in countries with low labour costs.

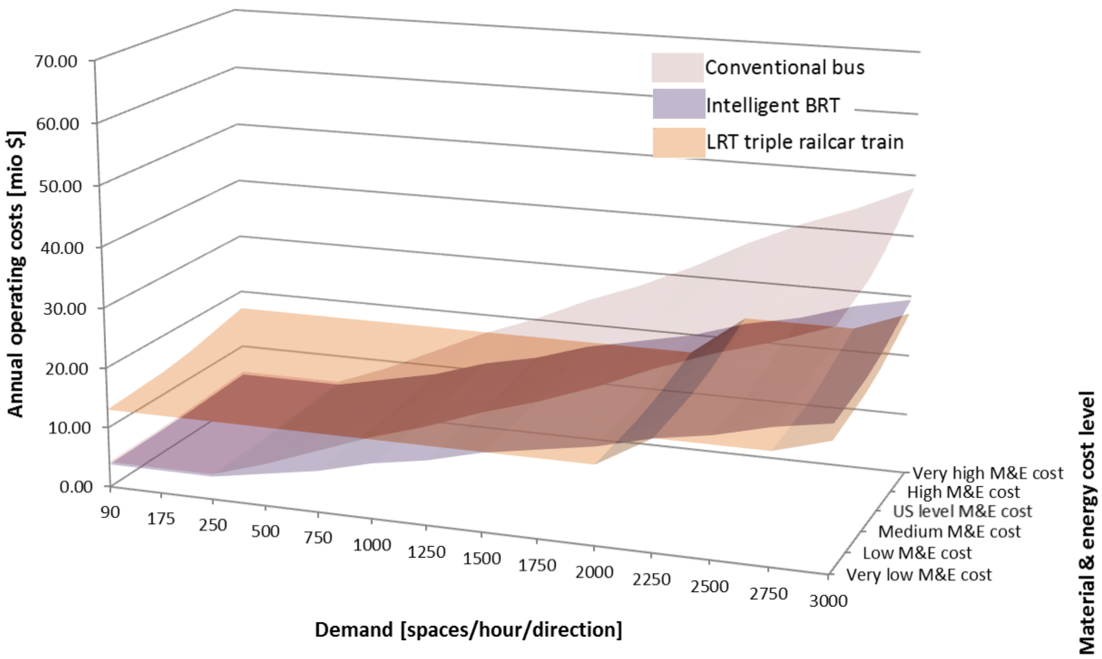
Figure 27 Annual operating costs of conventional bus, BRT, and LRT for different labour cost scenarios



5.3.7 Energy & material cost levels

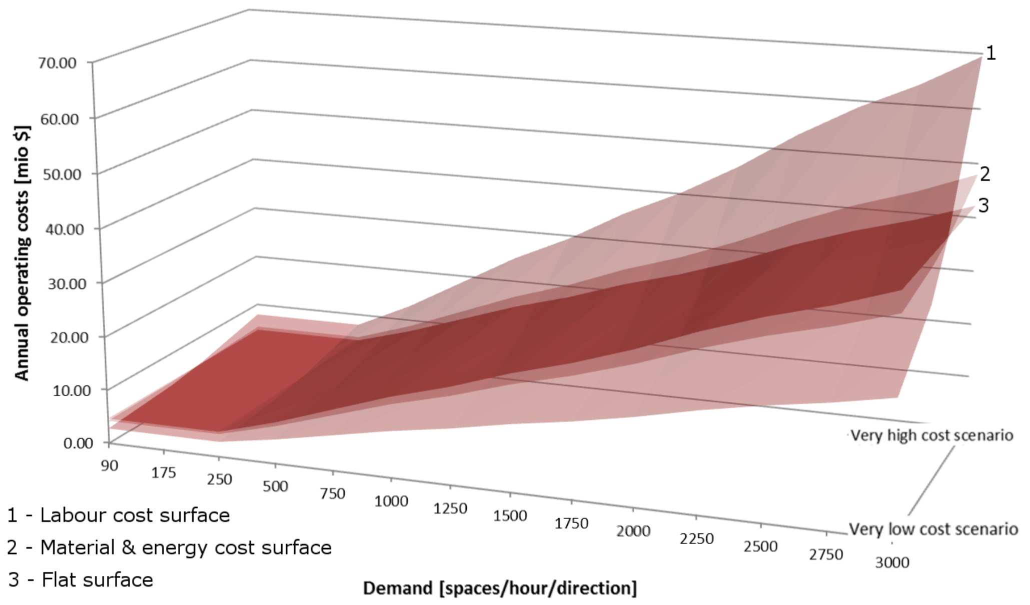
This chapter uses the above model by Bruun (2005) to analyse the influence of energy and material costs on the thresholds between transport modes. Figure 28 shows the cost-capacity surfaces of conventional bus, intelligent BRT, and triple railcar LRT trains for different energy & material cost levels. To reach these cost scenarios, the input parameters of fuel and tires costs per bus-kilometre (C_{BK}), as well as propulsion power costs and "expendables specific to rail technology" (C_{CK}) for one railcar-kilometre were manipulated. In analogy to the analysis of labour costs, five scenarios were calculated. Scenarios of very low, low, medium, and USA level energy & material costs are obtained by dividing the USA cost figures respectively by 3, 2, 1.5, and 0. The high and very high energy & material cost scenarios are obtained by multiplying the USA cost figures respectively with 1.5 and 2. The unit costs of energy & material consumption for one bus-kilometre vary between 1.12 and 2.15 US$ in the lowest and highest cost scenarios. The according variation for one railcar-kilometre is between 1.53 and 2.85 US$. Despite of this large variation in per-kilometre costs, the observed variation of total annual operating costs in Figure 28 is relatively small for all modes and the cost – capacity equilibrium points between modes do not change substantially in different material & energy cost scenarios.

Figure 28 Annual operating costs of BRT classes for different material & energy cost levels



This result contrasts the previously discussed strong variation of the equilibrium points for different labour cost levels. The finding that material & energy costs have a much smaller influence on operating costs than the labour cost level is clarified in Figure 29. In this diagram, the effects of labour cost levels are compared to material & energy cost levels, using the example of conventional bus operation. Obviously, the inclination of the labour cost surface is much greater than the inclination of the material & energy cost surface, both in relative and absolute terms when compared to the flat cost surface. This indicates that changes in labour costs affect the choice of the most cost-effective transport mode far more than changes in the material & energy cost level.

Figure 29 Material & energy cost and labour cost scenarios in conventional bus operation



5.4 Additional selection criteria for public transport modes

Apart from quality, capacity, and cost-efficiency considerations, other factors affect the choice between transport modes. Table 15 provides an overview of additional criteria that affect the choice of mode when planning or extending a public transport system.

Table 15 Additional selection criteria for PT modes

Criterion	Description
Use of street space	The consumption of street space to provide a given capacity varies between transport systems. The above example of triple railcar LRT trains would require stations with a length of 84m, which might not be possible in all urban contexts. However, BRT stations and terminals with passing capability also require large street spaces. The availability of street space has to be analysed for each individual project.
The rail-bonus and ridership generation	Vuchic (2005, p. 524) states that rail rapid transit and LRT lines can attract greater numbers of passengers than does a typical bus route. However, Scherer (2011) found that in the case of Switzerland, the images of bus and tram systems are not perceived as significantly different. Thus, it remains unclear of whether the use of rail technology leads to a higher ridership generation. White (2002, p. 59) even identifies a rail-bonus for guided bus systems and indicates that this phenomenon probably occurs because of the higher speed and riding comfort of guided systems.

Ability to create networks	In many cases, new PT systems are constructed neighbouring already existing transport systems. In these cases, it might be favourable to design a new system that is compatible to existing systems to benefit from economies of scale and to allow for through operation. An advantage of BRT systems is that in many cases, vehicles are compatible with conventional bus operation. A particular advantage of using low-floor BRT vehicles is the possibility of branching them onto selected tangential or feeder routes when they reach their capacity limit (Bruun, 2005, p. 20). This is an advantage of BRT light and understatement BRT above heavy infrastructure BRT and some intelligent BRT with more specialised and often high-floor vehicles and stations. In addition, the latter two BRT classes are mostly used to serve selected trunk corridors whereas BRT light and understatement BRT in most cases form networks. Hence, the ability of forming new networks or integrating into existing bus systems is an argument for choosing BRT light and understatement BRT above heavy infrastructure BRT or LRT systems.
City size and density	Giannopoulos (in Grava, 2003, p. 303) suggests that in general, conventional bus systems are sufficient for urban areas below a population of 200,000. In communities with a low density, he argues that this boundary line may go up to at least 1 million. Accordingly, it could be argued to base the mode choice upon city size and density.
Implementation time	It is often argued that rail-based systems need a long time from the planning to implementation stages. This might be true, but in some cases, the implementation of BRT systems has also required several years, such as in Santiago (Chile) or Lima (Peru). Hidalgo et al (2010a, p. 21) conclude that political commitment plays a key role in the overall speed of project planning and implementation. Accordingly, the mode-specific implementation time is probably less important than the political will that determines the required development cycles.
Land use development	Levinson et al. (2003) identify land use development benefits of BRT systems. In the case of Brisbane (Australia), property values near the busway gained up to 20% and in Pittsburgh (USA), the land development benefits added up to around 300 million US$ close to BRT stations. Accordingly, BRT systems have a clearly positive impact on land use development, along with rail-based systems. The amount of these advantages has to be evaluated in the individual case.
Culture	General preferences of decision makers and the broad public influence the decision on transport modes. In some cases, the possibility to implement BRT systems within a relatively short time can open windows of opportunity, for example if the completion is possible before the end of the term limit of supportive elected officials (Hidalgo et al., 2010a, p. 21).

5.5 The general picture: a qualitative mode comparison

Table 16 completes the above quantitative mode comparisons with a qualitative overview. The table provides a rough oversight of strengths and weaknesses of different transport modes. It becomes clear that rail-based modes have advantages in most quality criteria as well as in capacity. In contrast, bus-based systems offer potentially lower costs. BRT systems occupy a niche between conventional bus systems with a low cost and a low quality and rail-based systems with a high quality and higher costs.

Table 16 Qualitative mode comparison

		Transport mode								
		Informal public transport	Conven-tional bus	BRT light	Under-statement BRT	Intelligent BRT	Heavy infra-structure BRT	Tram	Light rail transit LRT	Heavy rail
Quality criteria	Availability	good	fair	good	good	good	good	good	quite good	fair
	Accessibility	poor	fair	good	very good	good	very good	very good	very good	very good
	Travel time	poor	poor	fair	quite good	quite good	good	fair	good	very good
	Reliability	poor	fair	good	good	good	good	good	good	good
	User cost	largely independent of mode choice								
	Comfort	poor	fair	good	good	good	very good	very good	very good	very good
	Safety	poor	fair	good	good	good	good	very good	very good	very good
	Security	very poor	largely independent of mode choice							
	Image	very poor	poor	fair	good	good	good	very good	very good	good
	Customer care	very poor	largely independent of mode choice							
	Environmental impact	very poor	fair	good	good	good	good	very good	very good	good
Cost-efficiency criteria	Investment cost	low	low	low	low	quite low	quite low	high	high	very high
	Operating cost	lowest for low passenger volumes				lowest for medium passenger volumes		lowest for high passenger volumes		
	Opportunity cost	low	low	quite low	medium	medium	medium	high	high	very high
	Land use development effects	none	none	few	few	good	good	good	very good	very good
	Capacity	poor	fair	fair	quite good	quite good	good	good	good	very good

Source: Vuchic (2005, p. 591), modified.

5.6 Chapter review

Calculations using cost figures from the USA indicate that BRT is a viable option especially for demand levels between ca. 250 and 3000 spaces per hour per direction. Main factors affecting the threshold levels between modes are commercial speed, unit capacity, the local labour cost level, and minimum quality requirements (such as a minimum frequency of service or a maximum vehicle load factor). Increasing commercial speed (by reducing interference with other traffic) and capacity (by using larger vehicles) are measures to improve the potential of the BRT mode. BRT proves to be especially favourable in situations with a low labour cost level, where frequent services are desired, and where high vehicle load factors are tolerated. This is an argument to implement BRT systems especially in developing countries with low labour cost levels. Inversely, it implies that LRT systems should be considered already at a lower demand in countries with high labour cost levels. In addition, LRT offers potential advantages in cases where off-peak demand is expected to increase over years. In general, an improvement in the frequency of service becomes more costly with increasing labour cost levels. In other words, the economies of scale from operating larger vehicles are more substantial if the labour cost level is high.

Further findings are that surprisingly, speed improvements in bus operation are even more important than in the case of rail since in bus systems, they seem to contribute even more in the reduction of annual operating costs than they do in the case of rail-based systems. In addition, bus modes seem to be relatively more competitive compared to LRT if vehicles are allowed to fill up to capacity than if only a limited occupancy is tolerated. The inclusion of energy and material costs showed that changes in the labour cost level affect the choice of a cost-effective transport mode far more than changes in energy and material costs.

In general, BRT systems occupy a niche between conventional bus systems with a low cost and a low quality and rail-based systems with a high quality and higher costs.

6 Improving BRT systems

Chapter outline: in this chapter, success factors and ways to improve BRT systems will be summarised. For this purpose, different BRT case studies will be analysed to identify successful and less successful examples. These case studies will be combined with the findings from the above chapters to identify success factors of the BRT mode and situations in which the use of other modes should be considered.

6.1 Case studies and success factors

In most cases, the implementation of a BRT system is followed by an evaluation, which identifies success factors and critical elements. A non-representative selection of system evaluations is presented here, providing an insight into elements that in practice have contributed to the success of system examples. A global measure of success could be the degree to which a public transport system meets the requirements of all groups of actors. Hence, a successful system does not only perform well in terms of quality that is perceived by users, but also in terms of capacity, cost-efficiency, and external effects. Success is not only expressed in objective numerical and monetary units, but especially the quality of service is valued and perceived by individuals. As a result, the judgement of whether or not an individual system is a success is always influenced by underlying expectations and the comparison to formerly existing public transport systems.

6.1.1 Success stories

Curitiba and Bogotá

The statement by Grava (2003, p. 392) that Curitiba is “the Mecca and Lourdes for transportation planners” leaves no question about the success of this BRT system. Ardila Gómez (2004, p. 32) observes that the Curitiba and Bogotá BRT systems have been extensively used as showcase examples around the world and considers this fact to be an indicator of success. Wright et al. (2007, p. 22-25) state that the implementation of Curitiba’s BRT system substantially propelled the career of the responsible mayor and political backer of the original concept, Jaime Lerner. After the introduction of the BRT system, he was elected twice as the mayor of Curitiba and as the governor of Paraná, which would hardly have been possible if the system was considered to be a failure. After the implementation of the TransMilenio system, Bogotá has hosted major public transport conferences and received technical missions from a range of cities. Wright et al. indicate that many cities from all continents have started BRT efforts after having studied the Curitiba and Bogotá examples.

London

Despite of not being a BRT system, London is an example of a successful bus system, which caused demand to rise constantly over the past ten years, contrasting other cities in the United Kingdom. Its success is based upon four broad goals of service quality: frequency, reliability, comprehensiveness, and simplicity. Various features have been implemented that contribute to the accomplishment of these objectives: the frequent use of well-demarcated and strictly enforced bus lanes, accessible low-floor vehicles for fast boarding and alighting, pre-board fare collection in central areas, real-time information displays at stations, driver training, and quality incentive contracts with concessioned operators. These measures have helped considerably in increasing average speed and overall reliability (paragraph based on Wright et al., 2007, p. 20).

Other positive reports

Hidalgo et al. (2010a) list general achievements that have been observed in many BRT systems. They conclude that in general, BRT systems greatly improve travel conditions and receive good ratings from users. Nearly all the systems provide a higher quality and capacity than the traditional systems they replaced. In general, services have become faster and more efficient, and led to environmental and social benefits, mainly in reduced energy consumption, less emissions and urban revitalisation. The above authors state that the conditions along the bus corridors have improved most dramatically in the cases of Curitiba, São Paulo, Bogotá, Pereira, Quito, and Guayaquil.

6.1.2 Critical voices

The BRT launch in Santiago

Probably one of the most known cases where the launch of a new BRT system caused problems is the Transantiago system in Santiago (Chile). Hidalgo et al. (2010a, p. 23) state that insufficient public information and education led to “chaotic conditions” in the Transantiago launch. In some cases, public protests even required “law enforcement”. These authors state that in Santiago (as well as in Quito and in the 2006 TransMilenio expansion in Bogotá), transport operators protested against the BRT system largely due to a lack of communication and engagement by city authorities. Muñoz et al. (2008) provide a detailed analysis of the issues that arose in the Transantiago launch. They mention that in the initial phase of the system, the buses were not equipped with the necessary technology, impeding the use of smart cards and the use of GPS monitoring technology. The construction of segregated bus-only streets and lanes was severely delayed and the increased bus speeds assumed in the system design could not be guaranteed. This was compounded by a series of elementary management errors by some of the incumbent companies, such as drivers who were unable to get to terminals in time to begin their shifts and rented buses that were in a bad condition and not properly inspected. All this led to massive queues at bus stops and transfer terminals, unacceptably long waits and load factors, extreme crowding on Metro services, slow operating speeds, reduced frequencies, extreme delay propagation, a general feeling of chaos that still lasted after the first nine months of operation, and political consequences. However, after the chaotic system launch, the government took action to introduce enclosed interchange facilities and exclusive bus lanes, to expand the bus fleet, and to provide stronger control mechanisms (Muñoz et al., 2008). Improvements during the first three years of operation were significant. By the end of 2009, Transantiago was finally perceived as providing a higher-quality service than previous operations (Hidalgo et al., 2010a).

The "ftr" system in Yorkshire

When the BRT system "ftr" was introduced in the district of Yorkshire (UK), a newspaper commented that with its purple-coloured vehicles, the ftr system was "nothing more than a fleet upgrade with a purple hair-dye" (Bateman, 2007). Clark (2006) reported that during the first days of operation, some of the new articulated vehicles got stuck or had to be withdrawn with electrical faults. Customers were reported to struggle with high-tech ticket machines, the fare was perceived as being too high, and the work to raise kerbs and remodel junctions "has prompted more than a few grumbles" amongst residents. Bateman (2007) adds that "the operator's claim about providing the comfort, style and convenience of a tram without the rails can be translated for greater brevity as: 'it's a bus'". According to these critical voices, the improvements in the quality of service appear not to be perceived and valued by the customers in a way that would justify the investments. On the contrary, the new system is perceived as being too expensive, too complicated, oversized and technically unreliable in comparison to the preceding conventional bus system.

Common problems

A common problem in North American BHLS systems has been that the improvements have only relied upon expensive vehicle technology to create a new system image. But if public transport priority is not addressed, the goals of service improvements and ridership generation can hardly be met (Wright et al., 2007, p. 20). Further general problems that have been observed by Hidalgo et al. (2010a) highlight the need for continued improvements. Firstly, in many BRT systems, buses are commonly overcrowded during peak travel times. Secondly, pavement conditions have often been an issue, either because existing roadway infrastructure was used without improvements, or due to faulty construction. Bus lane segregation devices in some cities (e.g. León and México City) deteriorated very quickly and required early replacement. Thirdly, advanced fare collection systems proved particularly difficult to implement, because implementation schedules in many cities were too short to adapt software applications to local conditions. A critical issue in most cases has been to maintain a high operational quality of systems at an affordable fare. Financial sustainability is threatened in several systems because fares were initially defined by political authorities without a sound and comprehensive calculation of cost and revenues. Heavy subsidies and financial difficulties for the operators have been the consequences of keeping fares low. Another common problem are limited maintenance funds. Often, the start of the operation of a new system was rushed due to political considerations and took place without all the planned elements in place. This often led to initial problems, which mostly improved within the first few months of operation (section based onHidalgo et al., 2010a).

6.1.3 Success factors

Based on the analyses in this work, the following success factors of BRT systems can be identified:

- A high commercial speed.
- Realistic demand projections and an application of the mode at appropriate demand levels. The BRT mode proved to be especially favourable if demand is between ca. 250 and 2000 spaces per hour per direction. Above or below these thresholds, conventional bus or rail-based modes should be evaluated.
- The provision of a sufficient capacity by using appropriate vehicles. Bi-articulated vehicles are useful in cases where a maximum capacity is required. Enhanced standard vehicles are useful if the system is mainly aimed at quality improvements.
- Fares should be fixed at a realistic level and not out of political considerations to guarantee a financially sustainable operation.
- The involvement by city authorities and previous transport operators is a key factor for the success of systems and strongly affects the required time for implementation.
- If a system is branded as a new tier of service, the distinction from conventional bus operation has to be strong enough to be perceived by the general public. Otherwise, expectations are not met and the system is not perceived as being successful.

- The planning has to consider available street space, especially if a high capacity is desired. Bus infrastructures allowing for a high capacity can be very space-consuming.
- Tests prior to starting operation should check the functioning of new technologies to avoid problems in the initial phases of operation.

Hidalgo et al. (2010a) identify a number of additional success factors at the institutional, planning, decision-making and implementation level, which would go beyond the scope of this work. Recommendations at the design and implementation level include the following:

- Implement gradually, adapting the project on the basis of initial demonstration experience, such as a demonstration corridor.
- Use existing right-of-way to reduce land acquisition and involuntary displacement.
- Use sound engineering design to produce adequate infrastructure; pay special attention to pavement design and construction to avoid rapid deterioration.
- Wherever possible, minimise the negative effects on mixed-traffic flow as increased traffic congestion can create criticism and jeopardise support for the bus improvement.
- Involve the community in the implementation through adequate information and various participation and engagement programs.
- Restructure or transform existing bus operation so it can complement rather than compete with the new system.
- Pay attention to the system's image, through public information, user surveys, and careful maintenance of fixed infrastructure and vehicles.
- Adhere to operating contracts and avoid continuous renegotiation.
- Integrate the system development with other transport initiatives such as the construction of facilities for non-motorised transport and pedestrians.
- Have a clear vision for system expansion.

6.2 When to improve and when to consider other modes?

Several BRT systems are currently reaching their capacity limits. This lowers the quality levels and potentially increases operating costs. In these cases, the question arises if the respective BRT system should be improved, or if it should be replaced by a rail-based alternative.

6.2.1 Thresholds between modes

If the capacity limits of the BRT mode are reached in a system and negative consequences in terms of quality and operating costs begin to show, alternatives have to be considered. One alternative is to construct parallel BRT corridors or additional lanes if the capacity in one corridor is reached. In Quito, three separate BRT corridors are running in parallel streets for a considerable part of their course. However, the unfortunate lack of integration between these corridors led to the situation that the newly constructed corridor Central Norte hardly contributed in alleviating the capacity issues on the trolleybus BRT corridor from 1995, where ideas for an upgrade to a rail-based system have been recorded for years (Hidalgo et al., 2010a). Vuchic (2005, p. 530) states that in general, operating one corridor with a high frequency and capacity is the superior alternative to parallel corridors with a lower frequency since users generally prefer higher frequency over shorter access.

The higher threshold: deciding between BRT and rail-based systems

Disregarding the factors affecting operating costs, a generally appropriate range of application of BRT systems is at demand levels between ca. 250 and 2000 spaces per hour per direction. If demand considerably exceeds this upper demand threshold level, capacity, operating costs, reliability, commercial speed, comfort, and space-consumption considerations become an issue. Even though chapter 4.5.2 showed that bus-based systems can achieve capacities above 20,000 s/h/d, the appropriateness of this mode must be questioned in these cases. Since the decision on modes always depends on a number of local and case-specific factors, this work can only provide the general recommendation that in cases where demand exceeds 2000 s/h/d, a very careful consideration and weighting should be undertaken if BRT really is the favourable alternative above rail-based systems.

The lower threshold: deciding between BRT and bus systems

The above newspaper articles about the "ftr" system in Yorkshire indicate that there are cases where the broad public is not convinced about the advantages of a BRT system in comparison to a conventional bus system. In fact, the higher capital and operating costs of a BRT system have to be justified by a real need to upgrade a conventional bus system and by a perceivable surplus that results for the customers. Otherwise, users will not accept to pay a higher fare or to contribute through their taxes, and financial sustainability of the system is put at stake. Therefore, it can be concluded that before upgrading a conventional bus system to BRT, the question must be raised if the demand really justifies an increase in capacity and if improvements in conventional bus operation would not be sufficient in achieving an appropriate quality of service level.

6.2.2 Improving BRT systems

If replacing a BRT system by a rail-based alternative is not an option even though BRT reaches its limits, measures to improve capacity and quality of service should be considered. The above chapters of this work indicated which measures contribute in improving BRT systems, and a summary is provided here. The analysis of empirical data showed that it depends heavily on the BRT class which aspects need to be improved in the individual case. For example, heavy infrastructure BRT systems often have a high capacity but a low operating speed and reliability. Accordingly, improvements in this BRT class should focus on ROW and vehicle prioritisation and less on adding more vehicles. In contrast, intelligent BRT systems often offer a high speed but a low frequency. In these systems, capacity can be increased by adding more vehicles to increase the frequency of service. Two important approaches to improve BRT systems are:

- Commercial speed and reliability can be increased by reducing interference with other traffic, by shortening station dwell time, and by increasing station spacing and average headway. Concrete measures include the use of segregated running ways, vehicle prioritisation technology, off-board fare collection, and appropriate station and vehicle design. These measures reduce not only operating costs, but also increase capacity and quality of service.
- Capacity can be increased by using larger (e.g. bi-articulated) vehicles. This is an appropriate measure especially in cases where labour costs are at a medium to high level and where sufficient street space for constructing longer stations is available. The use of larger vehicles in these cases offers lower operating costs than adding more standard buses.

In addition, several authors have proposed ways to improve BRT systems. Hidalgo et al. (2010a, p. 31-32) deliver comprehensive recommendations to improve BRT systems, including the following:

- Prefer median lanes and level access platforms with many bus boarding doors to increase speed and reliability.
- Use strong lane dividers to segregate traffic.
- Design vehicles (e.g., their size, internal configuration, number of doors and configuration) and other physical features according to the market and the service plan.
- Match service operations to supply and demand, using the intrinsic flexibility of buses. For example, allow departures from the fixed route, introduce mid-way returns, and operate express services.

- Use advanced transit management systems if operations are complex, and apply them as tools to control reliability, not just as a means of acquiring operational data.

Is there an optimal BRT system?

The question could be raised if a combination of the successful elements of all BRT classes that have been identified in this work would lead to an optimally performing BRT system. For example, if the capacity of heavy infrastructure BRT systems could be combined with the high speed of intelligent BRT systems and the low cost of BRT light, the resulting system would have a very high performance level. In practice, a generally defined optimal system combination is of limited use since requirements, constraints and objectives vary largely between individual cases. Instead of defining an optimally performing BRT system in a general way, local performance requirements have to guide the planning process in each case.

6.3 Chapter review

From looking at system examples, it can be concluded that in general, BRT systems have greatly improved travel conditions and usually receive good ratings from users. Nearly all the systems provide a higher quality and capacity than the traditional systems they replaced. In general, services have become faster and more efficient, and led to environmental and social benefits, mainly in reduced energy consumption, less emissions and urban revitalisation.

Problems that have emerged are overcrowding during peak travel times and difficulties in implementing advanced fare collection technologies. A critical issue in many cases has been to maintain a high operational quality of systems at an affordable fare. Financial sustainability is threatened in several systems because fares were initially defined by political authorities without a sound calculation of costs and revenues. Often, the start of the operation of a new system was rushed due to political considerations and took place without all the planned elements in place. This often led to initial problems, which mostly improved within the first few months of operation. The case studies of Santiago (Chile) and Yorkshire (UK) confirm that particular care has to be taken in the initial phase of operation.

A generally appropriate range of application of BRT systems is at demand levels between ca. 250 and 2000 spaces per hour per direction. This work recommends that in cases where demand exceeds 2000 s/h/d, a very careful consideration and weighting should be undertaken if BRT really is the favourable alternative above rail-based systems.

Additionally, there are cases where the broad public is not convinced about the advantages of a BRT system in comparison to a conventional bus system. Before upgrading a conventional bus system to BRT, the question must be raised if the demand really justifies this increase in capacity and quality. If this is not the case, users will not accept to pay a higher fare or to contribute through their taxes, and financial sustainability of the system is put at stake.

Possible ways to improve BRT systems depend heavily on the BRT class. Improvements in heavy infrastructure BRT systems should focus on ROW and vehicle prioritisation. In intelligent BRT systems, capacity can be increased by adding more vehicles to increase the frequency of service. Commercial speed and reliability can be increased by reducing interference with other traffic, by shortening station dwell time, and by increasing station spacing and average headway. Concrete measures include the use of segregated running ways, vehicle prioritisation technology, off-board fare collection, and appropriate station and vehicle design. These measures reduce not only operating costs, but also increase capacity and quality of service. Capacity can be increased by using larger (e.g. bi-articulated) vehicles. This is an appropriate measure especially in cases where labour costs are at a medium to high level and where sufficient street space for constructing longer stations is available.

7 Synthesis

7.1 Conclusions

The findings of this work indicate that BRT has cost advantages over conventional bus and light rail transit (LRT) operation at demand levels between ca. 250 and 2000 spaces per hour per direction. Main factors affecting the threshold levels between modes are commercial speed, unit capacity, the labour cost level, and quality requirements (such as a minimum frequency of service or a maximum vehicle load factor). BRT proves to be especially favourable in situations with a low labour cost level, where frequent services are desired, and where high vehicle load factors are tolerated. This is an argument to implement BRT systems especially in developing countries with low labour cost levels.

Findings of this work indicate that in comparison to conventional bus operation, BRT systems allow for quality improvements mainly in terms of capacity, accessibility, comfort, safety, and image. However, data from real-world examples indicate that in many BRT systems, further effort is needed to increase commercial speed and reliability.

Commercial speed and reliability can be improved by reducing interference with other traffic, by shortening station dwell time, and by increasing station spacing and average headway. Concrete measures include the use of segregated running ways, vehicle prioritisation technology, off-board fare collection, and appropriate station and vehicle design. These measures increase the capacity and quality of service and reduce operating costs.

The capacity of BRT systems can be increased by a higher level of segregation from other traffic, by using larger vehicles, by operating at higher frequencies, or by lowering the comfort standard. However, not all BRT systems are targeted at delivering a maximum throughput. In many cases, demand does not justify an operation at the capacity limit. The below listing gives a short summary of findings:

BRT is an alternative in cases where:

- Demand is ca. 250 – 2000 spaces per hour per direction.
- Labour cost levels are low and not expected to rise, where frequent services are desired, and where high vehicle load factors are tolerated.
- Quality improvements (to conventional bus) are desired mainly in accessibility, comfort, safety, and image.

- Relatively fast and inexpensive implementation is required.
- Enough street space is available.
- Commitment and political leadership are assumed by the city authorities.

BRT is of limited use:

- If a commercial speed above 30 km/h is required (normally).
- At demand levels below ca. 250 or above ca. 2000 spaces per hour per direction.
- As a means of mass transport if labour cost levels are rising.
- If very narrow urban situations impede the use of surface transport systems.
- If it is not distinguished sufficiently from conventional bus systems.

7.2 Relevance of the results

7.2.1 Significance in relation to previous work

In their suggestions for future work, Hidalgo et al. (2010a, p. 33) identify the performance of BRT systems and thresholds between modes as key areas for further research within the BRT topic. They state that a detailed review of how the design and operation of BRT systems relate to operational efficiency would be helpful. They further identify the need for objective analyses and case studies to identify situations where a certain mode of transport should be selected for implementation since too many decisions have been made based on ideological arguments or commercial interests. By evaluating different system designs (BRT classes) for their performance and by identifying thresholds between modes, this work occupies its niche within this research space. In general, this work contributes to developing a more informed and objective decision-making process about which mode should be considered in a given situation and which factors and circumstances might affect the appropriateness of implementing a given transport mode. The approach of using a parametric cost model for mode comparison allowed for a comparison of transport modes regarding different scenarios and permitted a comparison of quality aspects. However, the general findings from this work by no means replace detailed studies in each implementation case and care should be exerted in applying general statements to specific urban contexts.

7.2.2 Achievement of objectives

The main objective of this work, namely the provision of a better understanding of the limitations of BRT systems in urban areas, has been achieved to a large extent. The chapter about system performance additionally provided a thorough analysis of the elements influencing the quality levels of urban bus services. Nevertheless, temporal limitations impeded a more detailed evaluation of the assumptions of the parametric cost model and a calibration for different circumstances. Limitations in the quality of the empirical data impeded more exact findings regarding the quality of service of BRT systems. Due to temporal constraints, it was not possible to double-check all empirical data. A classification of existing systems was only made on the basis of system elements and it did not include the criteria of investment, benefit for the community, financing, sustainability dimensions, and the urban context, as suggested in the objectives of this work. The objective of analysing underlying cultural reasons for different quality of service levels was just slightly touched and is left to other authors (for example Ardila Gómez, 2004, for the cases of Curitiba and Bogotá). The task of providing a comparative analysis of BRT and rail-based modes was mainly performed on the basis of cost comparisons and a detailed analysis of influencing factors. The objective of comparing modes in terms of implementation time, benefits for the users, land use development effects, and cultural elements was addressed to a lesser extent.

7.3 Further research

Suggestion 1: validate the parametric cost model

The mode comparison by means of a parametric cost model allowed for the evaluation of threshold levels between transport modes regarding different scenarios. However, temporal limitations impeded a detailed evaluation of the assumptions of the parametric cost model by Bruun (2005) and a calibration of the underlying cost structures for different situations. This could be done by including cost structures and operating cost figures from real-world examples. By this means, the quality and relevance of the mode comparisons would doubtlessly increase. Validating the threshold levels for mode choice that have been identified in this work would be a useful field of further research since the provision of a more profound basis of these threshold levels would increase their credibility and impact on practical decision-making.

Suggestion 2: assemble a consistent base of BRT data

This work experienced severe constraints in the quality of the empirical data. These limitations impeded a more detailed analysis of the quality of service of BRT systems. Due to temporal constraints, it was not possible to double-check all empirical data or to collect missing values. A rough manual credibility check quarried some obvious inconsistencies that may originate from the fact that the data are compiled from various sources from all over the world. It is probable that inconsistencies partly result from using inconsistent definitions, mixing up measuring units, etc. The development of consistent and easily usable methods for

BRT data collection and the development of consistent, validated, and readily available databases would greatly improve the evaluation of BRT systems.

Suggestion 3: extend the methodology for evaluating quality aspects

This work has demonstrated that a purely cost-based comparison of modes does not provide a satisfactory basis for mode choice, since quality of service varies greatly between modes. For the purpose of including quality aspects, further work is needed on defining the benefits resulting from quality advantages of individual transport modes. Despite the fact that methodologies for the valuation of quality aspects are already in use (an example of cost-benefit analysis can be found in Echeverry et al., 2005), they have to be developed further and extended to allow for a more informed choice between modes in the individual case.

Suggestion 4: use the multi-dimensional classification approach from this work to evaluate other aspects

In this work, BRT systems have only been classified on the basis of system elements. The multi-dimensional classification approach on the basis of statistical cluster analysis from chapter 3 could also be used to assess differences between systems in the level of investment, benefit for the community, financing, sustainability dimensions, urban environment, etc.

Suggestion 5: analyse the usefulness of BRT systems at very high capacity levels

Chapter 4.5 of this work showed that there are BRT systems offering a capacity of far more than 5000 spaces per hour per direction. Further research is needed on the cost structure of BRT systems to assess the cost-efficiency of BRT operation at such high capacity levels. This is necessary because findings of this work indicate that BRT operation at such high capacity levels might prove to be problematic form a cost-efficiency and quality of service point of view.

Suggestion 6: further work on organisational and planning issues

This work identified organisational and planning elements as critical success factors for BRT implementation. Although this was not a key field of this work, the suggestions by Hidalgo et al. (2010a, p. 33) are repeated here to intensify the work on governance issues, institutional barriers and solutions, financial structures, sources of funding, and public participation.

8 References

Ardila Gómez, A. (2004) Transit planning in Curitiba and Bogotá : roles in interaction, risk, and change, Massachusetts Institute of Technology.

Bateman, R. (2007) Ftr: it's (still) a bus, http://www.nouse.co.uk/2007/01/23/ftr-its-still-a-bus/, University of York's student website. Accessed: 04. April 2011.

Brader, C., D. Mobereola, R. Kaenzig (2010) Africa's First Bus Rapid Transit System, *Transportation Research Record: Journal of the Transportation Research Board*, **2193** (-1), 1-8.

Bruun, E. (2005) Bus Rapid Transit and Light Rail: Comparing Operating Costs with a Parametric Cost Model, *Transportation Research Record: Journal of the Transportation Research Board*, **1927** (-1), 11-21.

Cain, A., J. Flynn, M. McCourt, T. Reyes (2009) Quantifying the Importance of Image and Perception to Bus Rapid Transit, *Report FTA-FL-26-7109.2009.3*, U.S. Department of Transportation, Washington, D.C.

Carrasco, N. (2011) Quanitfying public transport reliability in Zurich, *11th Swiss Transport Research Conference (STRC)*, Institute for Transport Planning and Systems IVT, ETH Zürich, Monte Verità, Ascona.

CEN (2002) EN 13816, European Committee for Standardization CEN, Brussels.

Clark, A. (2006) The rise of the purple people-eaters, *The Guardian*, 15. May 2006, London and Manchester.

Currie, G. (2005) The Demand Performance of Bus Rapid Transit, *Journal of Public Transportation*, **8** (1), 41-55.

Diaz, R.B., D. Hinebaugh (2009) *Characteristics of Bus Rapid Transit for Decision-Making (CBRT).* U.S. Department of Transportation, Federal Transit Administration, Washington, DC.

Echeverry, J.C., A.M. Ibañez, A. Moya, L.C. Hillón (2005) The Economics of TransMilenio, a Mass Transit System for Bogotá, *Economia*, **5** (2), 151-196.

Grava, S. (2003) *Urban transportation systems: Choices for communities*. McGraw-Hill, New York.

Haseldine, P. (2007) Picture of El Trole BRT in Quito (Ecuador), www.tramz.com/ec/q/b31.jpg, Quito. Accessed: 13.6.2011

Hidalgo, D., A. Carrigan (2010a) Modernizing public transportation - Lessons learned from major bus improvements in Latin America and Asia, EMBARQ The WRI Center for Sustainable Transport, Washington, D.C.

Hidalgo, D., L. Gutierrez, L.A. Lindau (2010b) Status of the BRT Industry, *BRT-ALC Center of Excellence Meeting*, EMBARQ, The WRI Center for Sustainable Transport, Washington DC.

Highway Research Board (1965) *Highway Capacity Manual*. National Research Council (U.S.). Highway Research Board, Washington D.C.

http://dbpedia.org (2011) Image of the Leeds guided busway, http://dbpedia.org/page/Ipswich_Rapid_Transit. Accessed: 2.6.2011

http://www.academic.ru/ (2011) Image of the Caen tramway, http://de.academic.ru/pictures/dewiki/116/tramway_de_caen_station.jpg. Accessed: 18.4.2011

Kim, C.K. (2010) Transportation in Seoul for Sustainability, Seoul Metropolitan Government, Seoul.

Kittelson & Associates Inc., KFH Group Inc., Parsons Brinckerhoff Quade & Douglass Inc., K. Hunter-Zaworski (2003) Transit Capacity and Quality of Service Manual, *TCRP Report 100*, US TCRP (US Transit Cooperative Research Program), Washington, D.C.

Levinson, H.S., S. Zimmerman, J. Clinger, S. Rutherford, R.L. Smith, J. Cracknell, R. Soberman (2003) Bus rapid transit, volume 1: Case Studies in Bus Rapid Transit, *TCRP Report 90*, US TCRP (US Transit Cooperative Research Program), Washington, D.C.

Light Rail Now Project Team (2009) Bogotá's TransMilenio "BRT": Mythology About Traffic Impacts, Carbon Credits, and Costs, http://www.lightrailnow.org/myths/m_bog_2009-09a.htm, Austin, Texas. Accessed: 2.6.2011

Litman, T. (2008) *A Good Example of Bad Transportation Performance Evaluation: A Critique of the Fraser Institute Report "Transportation Performance of the Canadian Provinces"*. Victoria Transport Policy Institute, Victoria.

Muñoz, J.C., J.d.D. Ortuzar, A. Gschwender (2008) Transantiago: the fall and rise of a radical public transport intervention, in W. Saaleh, G. Sammer (eds) *Travel Demand Management and Road User Pricing: Success, Failure and Feasibility*, chapter 9, 151-172, Ashgate, Aldershot.

Nationmaster.com (2011) Currency Statistics: PPP conversion factor to official exchange rate ratio for the year 2005, http://www.nationmaster.com/graph/cur_ppp_con_fac_to_off_exc_rat_rat-factor-official-exchange-rate-ratio. Accessed: 23.05. 2011.

NBRTI - National Bus Rapid Transit Institute (2011) US National Bus Rapid Transit Database, http://www.nbrti.org/evaluate.html, Tampa. Accessed: 7.4.2011

O'Sullivan, S., J. Morrall (1996) Walking Distances to and from Light-Rail Transit Stations, *Transportation Research Record*, **1538** (TRB, National Research Council, Washington, DC), 19-26.

Plater, D. (2007) Image of a train in India, http://www.brisbanetimes.com.au/news/travel/trains-offer-insight-into-india/2007/12/24/1198344918501.html. Accessed: 3.6.2011.

Rabuel, S. (2009) *Buses with a High Level of Service (BHLS): the French Bus Rapid Transit (BRT) concept - choosing and implementing the right system*. Certu - Centre for the Study of Urban Planning, Transport and Public Facilities, Lyon.

Rachdi, S. (2011) Tren urbano de San José - horario INCOFER, http://www.fahrplancenter.com/AIFFLAINCOFER.html. Accessed: 7.4.2011

Sauter, D. (2004) Image of Zürich, Limmatquai, www.20min.ch/news/zuerich/story/25492997, Zürich. Accessed: 3.6.2011

Scherer, M. (2011) The image of bus and tram: first results, *11th Swiss Transport Research Conference STRC*, Institute for Transport Planning and Systems IVT, ETH Zürich, Monte Veritá, Ascona.

Schramm, J. (2011) Picture of the Trogenerbahn, http://bahn.joernschramm.de/appenzell-st-gallen.html. Accessed: 2.6.2011

Scruggs, G. (2011) Image of the São Paulo BRT, http://ecpaplanning.org/2011/04/sustainability-on-the-urban-periphery-the-case-of-diadema/, Energy and Climate Partnership of the Americas Urban Planning Initiative, São Paulo. Accessed: 2.6.2011

URL (2011a) Picture of the Curitiba BRT, http://nexus.umn.edu/Courses/Cases/CE5212/F2008/CS3/CS3_files/image001.jpg. Accessed: 18.4.2011

URL (2011b) Picture of the Zürich Forchbahn LRT, http://www.getdomainvids.com/keyword/forchbahn/. Accessed: 30.5.2011

Vrtic, M., O. Meyer-Rühle, G. Abay (2000) *Sensitivitäten von Angebots- und Preisänderungen im Personenverkehr*. Bundesamt für Strassen, Vereinigung Schweizerischer Verkehrsingenieure SVI, Prognos, Bern.

Vuchic, V.R. (2005) *Urban transit operations, planning and economics*. Wiley, Hoboken.

Wardman, M. (2004) Public transport values of time, *Transport Policy,* **11** (4), 363-377.

Weidmann, U. (2008) Grundlagen der System- und Netzplanung, System- und Netzplanung des Personenverkehrs, *Vorlesungsskript System- und Netzplanung*, **Band 1.1**, chapter, Institut für Verkehrsplanung und Transportsysteme IVT (ETH Zürich), Zürich.

Weidmann, U. (2009) Unternehmensführung, *Vorlesungsskript Management und Systembetrieb*, **Band 4.1**, chapter, Institut für Verkehrsplanung und Transportsysteme IVT (ETH Zürich), Zürich.

Weidmann, U., N. Carrasco (2010) Marketing, Qualität, *Vorlesungsskript Systemführung, Marketing und Qualität*, **Band 4.2**, chapter, Intitut für Verkehrsplanung und Transportsysteme IVT (ETH Zürich), Zürich.

Weidmann, U., N. Carrasco, M. Scherer (2011) Pünktlichkeit im Stadtverkehr: Wie der Bus zum Tram werden kann, *Stadt und Verkehr*, Zürich.

White, P. (2002) *Public transport*. Spon Press, London.

Wright, L. (2003) Bus rapid transit, in K. Fjellstrom (ed) *Sustainable Transport: A Sourcebook for Policy-makers in Developing Cities*, Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Eschborn.

Wright, L., W. Hook (2007) *Bus Rapid Transit Planning Guide*, 3rd ed. Institute for Transportation & Development Policy, New York.

www.gobrt.org (2011) Image of Curitiba BRT, http://www.gobrt.org/db/uploads/expres13.jpg, Bus rapid transit policy center www.gobrt.org. Accessed: 2.6.2011

www.subways.net (unknown year) Picture of a tram jam in Kiev, www.subways.net/ukraine/kievtraffic.jpg, Kiev. Accessed: 3.6.2011

9 Glossary

Accessibility of a transport system is a measure for how easily passengers can access and use transport services. It includes the availability of necessary information, the physical access, the simplicity of movement inside the system and the availability of facilities to acquire or validate tickets. Accessibility is a part of the quality of service.

Availability of a transport system is a measure for the range and extent of the services on offer by reference to time and geography. If a transport system is not available, it is not part of possible alternatives for individuals when making the choice of which mode should be used for transport. Availability is a part of the quality of service.

Bus rapid transit (BRT) systems are qualitatively enhanced bus systems that aim at providing cost-effective urban transport with a strong customer focus, a high quality of service, a suitable capacity, and a beneficent social, economic, and environmental impact. This is achieved through a combination of high-quality vehicles, infrastructures, service and operation plans, branding elements, as well as operations management, vehicle prioritisation, and fare collection technologies, which are selected and specified individually for every implementation case, requiring well-organized and integrated planning. The term is sometimes used interchangeably with: high-capacity bus systems, high-quality bus systems, metro bus, surface subway, express bus systems, and busway systems (See Wright et al., 2007, p. 11).

A **Bus** is a self-propelled, rubber-tired road vehicle designed to carry a substantial number of passengers, commonly operated on streets and highways (Kittelson & Associates Inc. et al., 2003, p. 8-6).

A **Bus lane** is a demarcated part of the street surface reserved primarily for public transport vehicles. Bus lanes are not physically segregated from other lanes and can in some cases be restricted to a specific hourly schedule (Wright et al., 2007, p. 19).

A **Busway** is a physically segregated lane that is permanently and exclusively reserved for the use of public transport vehicles (Wright et al., 2007, p. 19).

A **Guideway** is a physically segregated bus infrastructure featuring mechanical or optical guidance technology to laterally guide vehicles with according technological guidance features (guide-wheels or optical sensors).

Heavy rail transit (HRT) is a rail-based urban public transport mode using trains of high capacity, operating in exclusive rights-of-way, usually without grade crossings, with high platform stations. The tracks may be in tunnels, on elevated structures, in open cuts, at surface level, or any combination thereof (based on Kittelson & Associates Inc. et al., 2003, p. 8-47).

Quality of service is the overall measured or perceived performance of transit service from the passenger's point of view, in terms of availability, accessibility, travel time, reliability, user cost, comfort, safety, security, image, customer care, and environmental impact.

Levels of service (LOS) are designated ranges of values for a particular service measure, based on passengers' perception of a particular aspect of public transport service. They are expressed on a scale, such as from "A" (highest) to "F" (lowest).

Light rail transit (LRT) is a rail-based urban public transport mode of single cars or short trains. Usually, it possesses exclusive rights-of-way at ground level, on aerial structures, in subways, or occasionally, in streets. Passengers usually board and discharge at track or car floor level. LRT is usually powered by electricity supplied by overhead wires (based on Kittelson & Associates Inc. et al., 2003, p. 8-47).

Performance is an output of a system, which can be quantitatively or qualitatively measured by performance indicators and indices.

Person capacity is the maximum number of people that can be carried past a given location during a given time period under specific operating conditions; without unreasonable delay, hazard, or restriction; and with reasonable certainty.

Public transport is a passenger transport service that is available to any person who pays a prescribed fare. It operates on established schedules along designated routes or lines with specific stops and is designed to move relatively large numbers of people at one time (based on Kittelson & Associates Inc. et al., 2003, p. 8-32). The term is sometimes used interchangeably with: transit, public transit, and public transportation.

A **Tram** or **Streetcar** is an urban public transport vehicle operating single cars or short trains on track in city streets in mixed traffic or on separated lanes, with stations close together. Streetcars are usually powered by electricity supplied by overhead wires. The term is sometimes used interchangeably with: trolley car (Grava, 2003, p. 809).

Transport is the act or process of moving people or things from one place to another. The term is sometimes used interchangeably with: transit, transportation (Webster's)

Transport mode is a term to distinguish substantially different ways to perform transport. Each mode uses a fundamentally different technology and requires a specific environment and infrastructures to operate. The term is sometimes used interchangeably with: mode of transport, transit mode, transport modality, form of transport, and means of transport.

Transport systems are systems that perform transport tasks. A transport system can consist either of only one transport mode, or combine a variety of modes.

Vehicle capacity is the maximum number of vehicles that can pass a given location during a given time period.

Note: where it is not indicated differently, these definitions have been compiled from Kittelson & Associates Inc. (2003 p. 1-7, 1-16, 1-17 and 3-1), EN 13816 (CEN, 2002), and Grava (2003, p. 1).

Annex

A 1 Exact reproduction of pre-defined background and tasks of this master thesis

This is a literal reproduction of the background and the list of tasks that were defined by the supervisors of this work.

Background

Historically, public transport services in urban areas worldwide have been mostly provided by common buses. Where the capacity needs and available resources justified it, rail-based solutions have been the common alternative. However, since the successful implementation of an integrated bus based system in Curitiba, Brazil in the late 1970 's, Bus Rapid Transit (BRT) systems have become a real alternative for many cities in need of alternatives to expensive rail-based systems. In the last decade, the world has seen an explosion in the numbers of BRT systems implemented in the five continents. Faster implementation times and lower investment costs than Light Rail Transit (LRT) and Metro systems are the main arguments of BRT advocates. There is no doubt that BRT systems are a step ahead in the quest for providing affordable and improved public transport for cities. However, rail-based systems are still a valid alternative for situations where the limits of a BRT systems could be reached, undermining the service to the passengers (delay, crowding, etc.) and the investments by cities. This raises the question of the limitations of BRT systems, and how they may play an important role in the quality of service provided. This work aims at exploring this question, focused mostly on capacity and quality of service issues. The expected result is a general guide of current ailings of BRT systems, and the provision of alternatives to either think of other modes, or improve current systems.

Work Package 1: BRT origins and evolution

A short summary of the origins of BRT, its evolution as a system, the trends in the last decades, current stand and future projects should be delivered. The main idea is to document the growth of the BRT phenomena and its geographical dispersion throughout a variety of urban areas. Relevant system characteristics and indicators should be summarized in a time scale. Additionally, examples of successful and less successful BRT systems should be identified, together with the reasons provided by the literature. Basic definitions should also be a part of this WP.

Work Package 2: System parameters and classification

Based on the literature, BRT, understood as a system, should be parameterized and classified. The different dimensions of BRT and the different possibilities of system configuration should be clearly documented in a generic form including examples. Sustainability dimensions provide a guide for classification, together with those found in the literature.

Work Package 3: System performance

This part of the work first addresses the stated problem of the thesis. The influence of the previously mentioned elements and parameters of BRT systems on quality of service and system performance should be described and analysed. Two perspectives should be addressed when required: that of the user, and that of the operator of the service, as often a certain trait is either positive or negative depending on who is looking at it. The influence of strategic and tactical planning, as well as operational practices and system context elements should be included in the analysis. In particular, the influence of public transit priority measures and right-of-way (ROW) should be analysed and discussed, as well as the causes of unreliability in public transport.

Work Package 4: Comparative analysis of BRT vs. Rail modes

Different types of BRT systems, as well as of rail modes should be included in a comparative analysis framework. The different systems should be compared in terms of performance, quality, service delivery, investment and operational costs, opportunity costs, affordability, implementation time, benefits for the users, reliability, safety, security, land use development effects, cultural elements, etc. The influence and impact of each system characteristic on the final quality of service should be analysed and discussed.

Work Package 5: Evaluation of possibilities for improving BRT systems

Based on the results of WP 4, those characteristics and parameters found to have a more significant impact on the quality of service should be analysed in detail. Threshold values between different systems should be identified. The reasons for success and failure of classic BRT systems identified in WP 1 should be discussed and related to the previous analysis. From the findings, the student should develop a generic guide of main problems and possible solutions for improving BRT systems. This guide should describe the problem or situation, the possible reasons, and the viable solutions with feasible benefits. Also, an idea should be provided of the limits of a given BRT system, and the situation in which another mode should come to mind.

A 2 Classification results with the alternative cluster method *furthest neighbour*

Figure 30 provides an overview of the results originating from a cluster analysis of the same data as in chapter 3.3, with the clustering method "furthest neighbour". The results show that a change in the clustering method results in a considerably different classification. Hence, the identification of BRT classes depends quite crucially on the clustering method and should accordingly be interpreted with care. The classification results for individual system examples are displayed in Table 17.

Figure 30 Hierarchical cluster analysis: results of method *furthest neighbour*

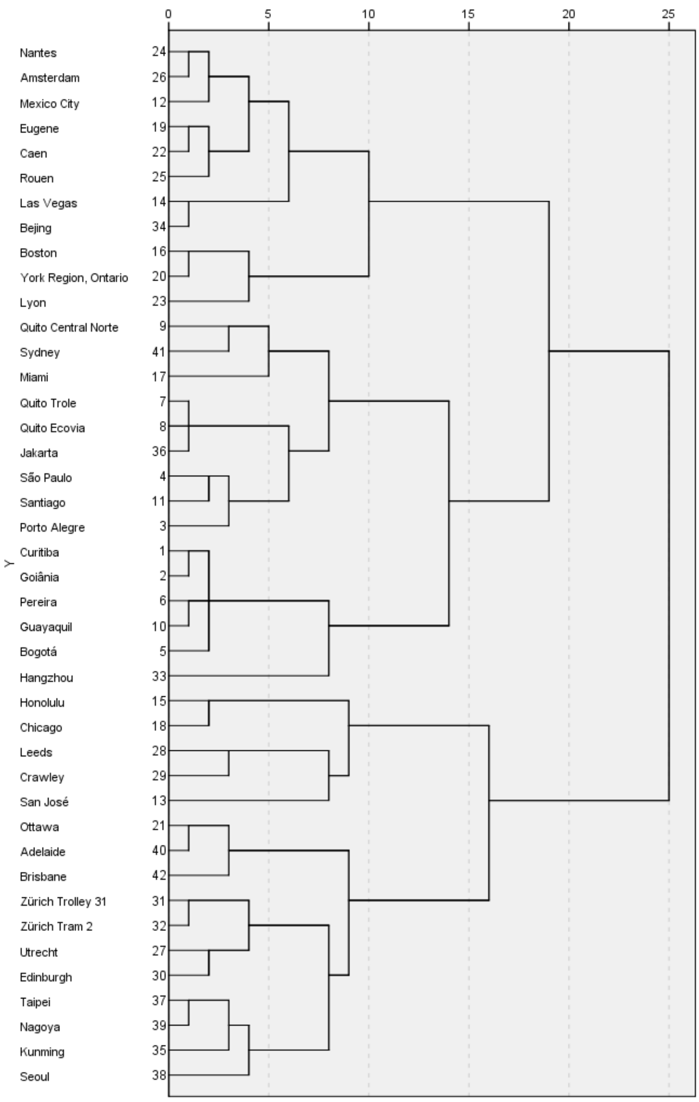


Table 17 Direct comparison of results between of the clustering methods *linkage between groups* and *furthest neighbour*

Method	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Linkage between groups	Curitiba, Goiânia, Bogotá, Pereira, Quito (Trole & Ecovia), Guayaquil, Hangzhou, Jakarta	Porto Alegre, São Paulo, Santiago, San José (Rail Service)	Quito (Central Norte), Mexico City, Las Vegas, Boston, Miami, Eugene, York Region (Ontario), Ottawa, Caen, Lyon, Nantes, Rouen, Amsterdam, Beijing, Adelaide, Sydney, Brisbane	Honolulu, Chicago, Utrecht, Leeds, Crawley, Edinburgh, Zürich (Trolley 31 & Tram 2), Kunming, Taipei, Seoul, Nagoya
Furthest neighbour	Curitiba, Goiânia, Bogotá, Pereira, Quito (Trole & Ecovia & Central Norte), Porto Alegre, São Paulo, Santiago, Guayaquil, Miami, Hangzhou, Sydney, Jakarta	Mexico City, Las Vegas, Boston, Eugene, York Region (Ontario), Caen, Lyon, Nantes, Rouen, Amsterdam, Beijing	San José (Rail Service), Honolulu, Chicago, Leeds, Crawley	Ottawa, Utrecht, Edinburgh, Zürich (Trolley 31 & Tram 2), Kunming, Taipei, Seoul, Nagoya, Adelaide, Brisbane

A 3 Key figures of BRT classes

The minimum and maximum values for some key indicators of BRT systems, divided in the four BRT classes, are listed in Table 18.

Table 18 Key figures of BRT systems in different classes

		Heavy infra-structure BRT	BRT light	Intelligent BRT	Under-statement BRT
System passenger-trips per day [million passengers]	Highest	1.45	2.78	0.26	0.156
	Lowest	0.04	no data	0.007	0.006
Peak ridership [p/h/direction]	Highest	45'000	35'000	10'000	12'000
	Lowest	1'500	no data	500	6'300
Length of trunk corridors [km]	Highest	84	129.5	80	86
	Lowest	9.4	no data	4	6
Number of stations	Highest	123	235	37	150
	Lowest	16	no data	3	9
Number of trunk routes	Highest	84	40	18	117
	Lowest	1	no data	1	1
Infrastructure costs [million US$/km]	Highest	9	10	53.2	46.5
	Lowest	0.45	no data	1.4	0.35
Average peak headway [min]	Highest	4	3	12	15
	Lowest	0.6	0.5	0.8	0.2