BUS RAPID TRANSIT (BRT) – A REVIEW

S.C.Wirasinghe, Professor

L. Kattan, Associate Professor

M.M. Rahman, Ph.D. student

J. Hubbell, Adjunct Associate Professor

R. Thilakaratne, Ph.D. student

S. Anowar, Ph.D. student

Department of Civil Engineering

Schulich School of Engineering

University of Calgary

Calgary

Alberta T2N 1N4

CANADA

1 Introduction

The success of sustainable urban transportation is based on selecting the optimal design and service aspects of a transit system that best meet and balance the needs of both operators and customers. A typical urban public transit planning process is concerned with providing a good level of service at a reasonable cost to the transit operator and to the users. A good level of service is provided by a transit system that is easily accessible in time (e.g., low waiting times) and space (e.g., low access distances), is reliable, requires a minimal number of transfers for a trip, and provides an affordable, safe, fast and comfortable journey with minimal environmental impact.

A variety of transit technologies are available for public transit, ranging from several bus modes to tram, light rail transit (LRT), commuter rail and metropolitan rail (metro) systems. There are few strict definitions of each transit mode. Within each transit mode, the design and service aspects may vary to produce the optimal solution for specific urban environments and service requirements. Bus rapid transit (BRT) is a bus mode that is being increasingly used across the world.

When greater speed or capacity is desired, there are numerous strategies that may be applied to influence passenger throughput and travel speeds. Articulated buses with multiple doors can be introduced, if additional capacity is required for essentially the same labor cost and bus dwell times need to be reduced to increase the mean speed. Bus dwell times can be further reduced by having electronic fare collection systems. The mean speed can be further increased by running the buses in bus-only lanes on regular roads.

The most basic characteristic of BRT is that it is a bus service operated on the basis of limited stops. When BRT is operating on separate rights of way, the system is called a busway. Though busways operate on an all-stop mode (as opposed to limited stops), the spacing of the stops is much larger than that of local buses. While not essential, modern BRT systems typically incorporate the use of information and communications technology, such as bus tracking through GPS (Global Positioning System), smart cards, traffic signal priority and electronic bus arrival time displays on board buses and at bus stands.

The main reasons for providing a BRT system are speed and capacity, although reliability is also usually increased. As a transit corridor evolves over time and regular all-stop type bus service reaches its limit, the corridor can be improved considerably by superimposing limited stop (BRT) service. BRT can have dedicated lanes on regular streets (thus reducing the capacity for private transportation) or a busway. A metro system is in a class by itself and is needed when the demand is expected to exceed the capacity of BRT and LRT systems and when much higher mean speeds are warranted.

Similar to other high-frequency transit modes, BRT has been shown to be successful in attracting high ridership from private automobile modes and to have environmental, social and economic benefits. However, these benefits may vary widely from one urban area to another, depending on the network characteristics, BRT characteristics, type of transit vehicles used, level of congestion, among other factors.

The introduction of a BRT or LRT system is based on the physical characteristics of a corridor, the current and estimated future passenger demand, and the financial capacity of the community at specific points in time. BRT may be selected as the desired transit mode to serve a corridor or it may be utilized as part of a corridor development strategy with higher order transit modes considered for the future. If the characteristics of LRT and BRT are well understood and the future demand for travel can be estimated with reasonable accuracy, the decisions regarding the technology to be used can be made in a rational manner. Thus, it is important to review each of these two modes in some detail.

In this paper, we review the characteristics of BRT systems. This paper covers some topics discussed by other reviews, e.g., Deng and Nelson (2011), Miller (2009) and Federal Transit Administration (2004), as well as several topics that have not been previously discussed. We take no side in the BRT versus LRT debate, but attempt to review BRT characteristics in a fair manner. LRT will be reviewed in a future paper.

2 A Brief History of BRT

It can be argued that the modern concept of bus rapid transit (BRT) was first implemented in Curitiba, Brazil, in 1974 as Rede Integrada de Transporte (RIT), which can be translated as Integrated Transportation Network (Weinstock et al., 2011). The success of the project inspired the implementation of many BRT projects. There are now about 146 cities with BRT systems or priority bus corridors around the world, serving nearly 24 million passengers per day (Global BRT Data, 2012).

Although there has been a greater emphasis on BRT in recent years, the BRT concept is not new. Plans and studies for various BRT-type alternatives have been prepared since the 1930s. For instance, BRT proposals were developed for Chicago in 1937, Washington D.C. between 1956 and 1959, and St. Louis in 1959 (Weinstock et al., 2011). The concept of BRT was first suggested in Chicago and called for conversion of three west-side rapid rail transit lines to express bus operation on freeways with on-street distribution in the central areas and downtown of Chicago (Harrington et al., 1937). In the years of 1955 to 1959, a Washington D.C. transit plan included design studies for an 86-mile BRT system, of which 42 miles were to be on special grade-separated busways (W. C. Gilman and Co., 1959).

A list of cities that have implemented BRT systems are shown in Figure 1. One of the early concept busways was placed on the Henry G. Shirley Memorial Highway in 1969 in Northern Virginia, USA (Grava, 2003). Runcorn opened its first busway corridor (an elevated section connecting to a retail center) in the UK in 1971. The 22-kilometer Runcorn busway played a significant role in reshaping the urban form (Wright, 2007).

Bi-articulated buses and tube-shaped stations were successfully used in Curitiba’s BRT system (i.e., RIT) in 1974 to expand corridor capacity. In 1980, Essen opened the first guided busway in Germany. The Ottawa Transitway opened in 1983, constructed primarily on a railroad right of way. It consisted of 60 kilometers of roadway, including 26 kilometers of bus-only grade-separated roadway, with most of the remaining distance on reserved lanes (Canadian Urban Transit Association, 2004). In Japan, the Key Route Bus System was introduced in Nagoya in 1985 to operate on an exclusive median bus lane.

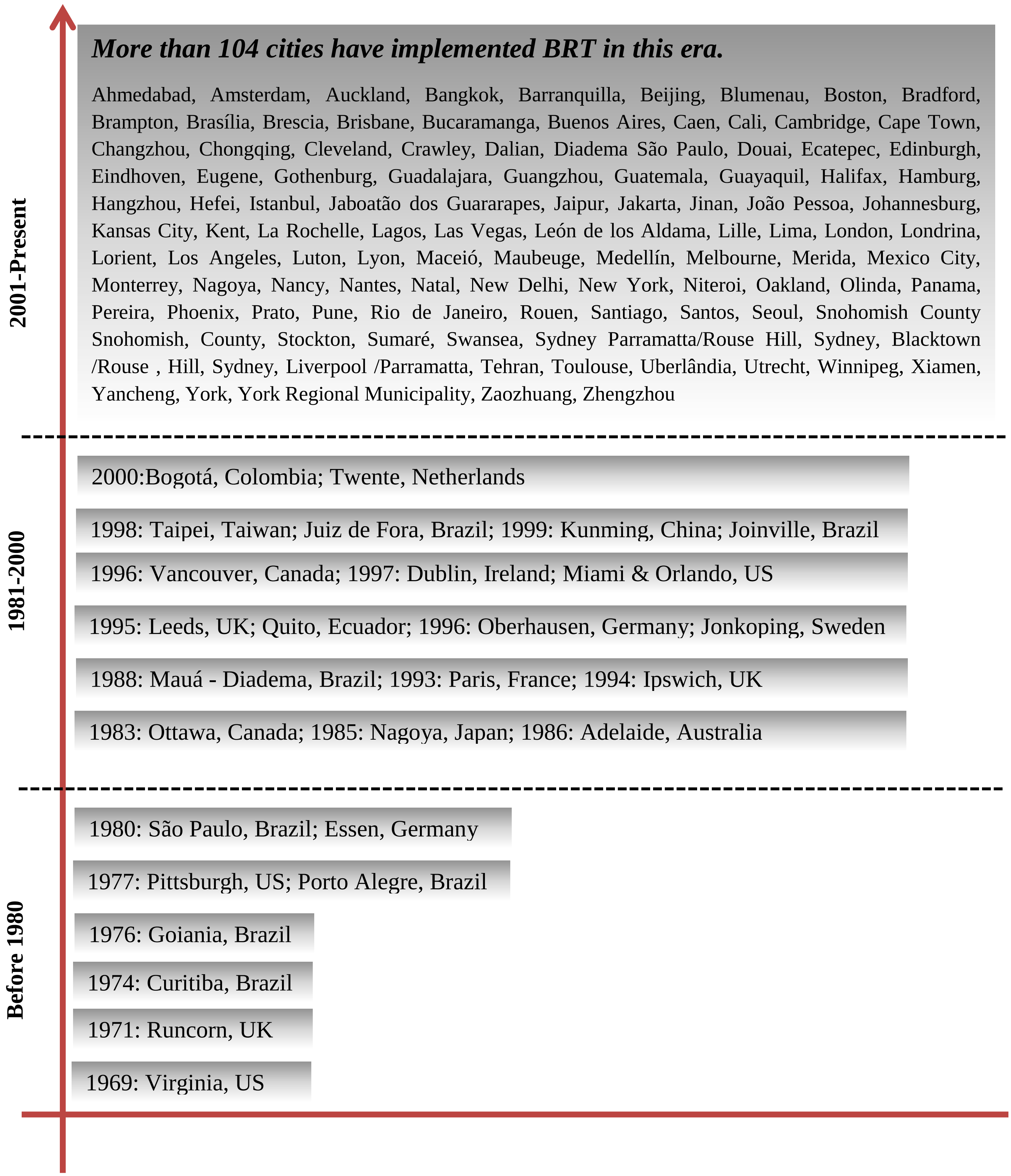

Figure 1. Evolution of BRT systems around the world

One of the world's longest and fastest guided busways was opened in Adelaide, Australia, in 1986 (Currie, 2006b). Australia also has some of the world's newest systems: the Brisbane Southeast Busway, the Brisbane Inner Northern Busway, the cross-corridor Sydney Transitways from Parramatta to Liverpool, and the cross-corridor Sydney Transitways Parramatta to Rouse Hill. These systems opened in 2001, 2004, 2003 and 2007, respectively.

TransMilenio of Bogotá, Columbia, which is a well-known BRT system, began operation in 2000. It is comprised of a dedicated busway, articulated buses, enhanced stations, a smart card based fare collection system, an advanced control system and an affordable ticket price. It has achieved impressive results in travel time savings, high passenger satisfaction, high capacity, accident and emission reduction, and operation without a financial subsidy (Cain et al., 2007).

Los Angeles' Metro Orange Line opened in 2005 and operates on a previously abandoned railroad corridor. This line is an advanced-featured BRT system, designed with characteristics similar to an LRT system, such as two dedicated lanes, automated ticket machines, fast boarding, and park and ride facilities. In China, BRT systems have recently been deployed in many cities, including Beijing, Changzhou, Hangzhou, Kunming, Ji'nan, Chongqing, Dalian, Xiamen, Hefei and Zhengzhou (Deng and Nelson, 2009).

Africa's first BRT system, BRT-Lite, opened in Lagos, Nigeria, in 2008. To provide a high-quality transport service for the 2010 World Cup Soccer tournament, the first phase of the Rea Vaya system opened in 2009 in Johannesburg, South Africa. To improve transport service, it used fully segregated bus lanes with prepaid platform-level boarding stations (Institute for Transportation and Development Policy, 2007; Walters, 2008).

BRT has now become a worldwide phenomenon; its current operation area around the world is shown in Figure 2 and Table 1.

Weinstock et al. (2011) have developed a tiered scoring scheme, the BRT Standard, aimed at ranking the performance of BRT systems. The BRT Standard allows BRT systems to be classified into three categories – gold, silver and bronze – that roughly reflect passenger travel time and quality of the service, based on speed and capacity and other indicators. Table 2 shows the criteria and weightings that were adopted as the BRT Standard according by the Institute for Transportation and Development Policy (ITDP). A total score of 85 or above classifies a BRT system as gold, a score of 70 to 84 as silver, and a score of 50 to 69 as bronze. ITDP reported the four highest ranking international BRT systems:

- Gold: Bogotá (93), Guangzhou (89)
- Silver: Johannesburg (79), Ahmedabad (76)

In the last decade, excellent BRT systems have rapidly emerged around the world, demonstrating that BRT can provide levels of speed and capacity comparable, in some cases, to some rail systems (Weinstock et al., 2011).

Figure 2. BRT systems around the world [Source: http://www.itdp.org]

Table 1. Global overview of the current BRT systems [Source: Global BRT Data, 2012]

Regions	Passengers / Day	Number of Cities	Length (km)
Africa	238,000	3	62
Asia	6,255,872	25	890
Europe	936,970	42	632
Latin America	15,067,311	49	1,183
North America	849,286	20	563
Oceania	327,074	7	328

Table 2. Definition of the BRT standard [Source: Weinstock et al., 2011]

Item	Max. Score
SERVICE PLANNING	
Off-vehicle fare collection	7
Multiple routes use same BRT infrastructure	4
Peak period frequency	4
Routes in top 10 demand corridors	4
Integrated fare collection with other public transport	3
Limited and local stop services	3
Off-peak frequency	3
Part of (planned) multi-corridor BRT network	3
Performance-based contracting for operators	3
Enforcement of right-of-way	2
Operates late nights and weekends	2
Operational control system to reduce bus bunching	2
Peak-period pricing	2
STATION DESIGN AND STATION-BUS INTERFACE	
Platform-level boarding	5
Buses have 3+ doors on articulated buses or 2+ very wide doors on standard buses	4
Multiple docking bays and sub-stops	3
INFRASTRUCTURE	
Bus lanes in central verge of the road	7
Physically separated right-of-way	7
Intersection treatments (elimination of turns across busways and signal priority)	4
Physically separated passing lanes at station stops	4
Stations occupy former road/median space (not sidewalk space)	3
Stations set back from intersections (100 feet min.)	3
Stations are in center and shared by both directions of service	2
QUALITY OF SERVICE AND PASSENGER INFORMATION SYSTEMS	
Branding of vehicles and system	3
Safe, wide, weather-protected stations with artwork (≥ 8 feet wide)	3
Passenger information at stops and on vehicles	2
INTEGRATION AND ACCESS	
Bicycle lanes in corridor	2
Bicycle sharing systems at BRT stations	2
Improved safe and attractive pedestrian access system and corridor environment	2
Secure bicycle parking at station stops	2

3 Elements of BRT System

BRT is considered an innovative and unique transit solution, because of the way it combines various facilities, services, amenities and technologies to create a higher quality of service. An in-depth understanding of the key characteristics of various BRT elements is crucial for planners, designers and developers. Diaz and Schneck (2000) indicated the following six major elements comprise a BRT system:

- Running ways / guide ways
- Vehicles
- Stations
- Fare collection systems
- Operations control systems
- Passenger information systems

The following subsections provide a detailed discussion of these elements.

3.1 Running Ways / Guide Ways

Running ways / guide ways are a BRT system's central elements and its infrastructural foundation (Levinson et al., 2003a). Although running ways for BRT can range from mixed traffic operations to fully grade-separated busways, these can be broadly categorized into three types: on-street, on-freeway and off-street (Xu and Zheng, 2012). On-street and on-freeway running ways include mixed traffic lanes, curb bus lanes, median bus lanes and bus-only streets. Off-street facilities are comprised of at-grade busways, bus tunnels and bridges. Several pros and cons are associated with each type of running way, and different types have been adopted in different parts of the world. For instance, it has been observed that providing separate or segregated running ways for BRT is a common practice in North America, while median arterial bus ways are widely used in South America (Levinson et al., 2003b).

BRT systems often operate in mixed traffic flow where geometric, traffic, land use, environmental or cost constraints can prevent implementation of fully dedicated bidirectional busways or bus lanes in residential locations. The advantages of operating in mixed traffic are low costs and quick implementation with minimum construction efforts. However, right-of-way constraints and traffic can result in reduced speeds and service reliability.

There are wide ranges of site-specific improvements that can help reduce operational delays: bidirectional lanes, reversible lanes and peak-hour-only exclusive lanes (Levinson et al., 2003a). Conceptually, a bidirectional BRT lane is an exclusive single lane in which BRT vehicles are allowed to pass through a constrained section. If another BRT vehicle is approaching from the opposite direction, it has to wait at a station or designated bypass area until the other vehicle has cleared the section. The associated signal system needs to be carefully designed to ensure that only one BRT vehicle occupies the constrained section at a time. In a recent study, Iswalt et al. (2011) found that a bidirectional lane can generate significant operating benefits for BRT vehicles and, at the same time, result in travel time savings for other modes and general traffic as well.

Reversible bus lane systems are similar to the bidirectional lanes. The direction of movement of the BRT vehicles depends on the direction of the peak hour traffic. Thus, BRT vehicles can be separated from peak period traffic and provided with priority. In other words, during a particular peak period, the BRT vehicles operate contraflow on a separate lane in the off-peak direction.

The restriction of a curbside general-purpose lane or parking lanes for the operation of BRT vehicles during the morning and evening rush hour traffic periods is another type of running way. Dedicated curb bus lanes are commonly used in central business districts and can operate at all times of the day. They are easier and less costly to implement, because only pavement markings and traffic signs are required. Other positive aspects of curb bus lanes are that they provide good pedestrian access and are more convenient to integrate with turns at intersections.

Dedicated curb bus lanes can be categorized into three types: concurrent or normal flow curb bus lanes, concurrent flow inside bus lanes, and contraflow curb bus lanes. The implementation of concurrent flow curb bus lanes is generally considered when other on-street BRT service options are not feasible. They are easy to implement and can operate during any time of the day. In order to eliminate the conflict between BRT vehicles and illegally parked vehicles along the curb, concurrent flow inside BRT lanes can be provided. These lanes are located adjacent to the curb parking lanes and thus allow curbside parking.

Contraflow lanes allow BRT vehicles to operate in the opposite direction of normal traffic flow. These types of guide ways are usually implemented on one-way streets and are self-enforcing. However, the conflicting direction of vehicular movements is confusing for pedestrians and may create safety hazards for pedestrians. Additionally, curb side lanes appear to be less effective in reducing travel times, due to frequent interference from general traffic, especially if right turns are allowed (Xu and Zheng, 2012).

Typically, median bus lanes are located in the center of the existing roadway and the direction of travel would depend on the travel environment and available space. The station platforms can be located in the centre or on the side. One of the primary benefits of such system is reduced construction costs, due to the utilization of existing medians (Rathwell and King, 2011). Moreover, the separation between transit and general traffic lanes can be accomplished through painted lines, rumble strips and/or mountable curbs. However, this type of running way is hard to enforce, due to continuous access.

Bus-only streets separate BRT from the general traffic and are warranted when there are higher bus volumes. One major advantage of this system is that it is easy to enforce. This design may also provide improved walking and movement space for pedestrians as well as waiting space for passengers. The removal of BRT vehicles from general traffic not only enhances the system's identity, but also improves the ambience of the surrounding area (Miller, 2009). General traffic may be moved to parallel streets.

All off-street running ways provide a physical separation of the BRT system from normal traffic. As a result, they allow for a faster travel speed of buses and minimize interference from and conflicts with general traffic. Therefore, these facilities not only enhance the efficiency of the system, but also provide a strong sense of the system's identity. For instance, Chen et al. (2007) found that simultaneous application of exclusive bus lanes and signal priority effectively improves the operational performance of a BRT system. High capital cost and extended construction periods are two disadvantages of these guide ways. However, once the infrastructure is developed and the ridership is formed, these facilities may provide an opportunity for future conversion to rail or other fixed guide ways.

3.2 Vehicles

Vehicles are the principal elements of BRT technology, and vehicle quality conveys BRT system identity and image. These can be configured with respect to the number and width of doors, internal layout, floor elevation, etc. According to Vuchic (2007), the following vehicle features are required and are most effective for improving the BRT service quality:

- Vehicle size and body structure: Vehicle size has a substantial effect on the infrastructure cost (Caicedo et al., 2012). In the case of BRT systems, the vehicle size length is not fixed and depends on ridership level and its variation during the day. The bus type can vary from conventional standard to full-sized articulated and/or bi-articulated vehicles.

- Doors: Increasing the number of wide doors for boarding and alighting reduces the service/dwelling time of buses. While wider doors can support multiple stream boarding and/or alighting, multiple doors also result in better distributions of passengers within the vehicle (Zimmerman and Levinson, 2004) and reduce the time spent getting to/from a seat from/to a door. Separate doors for boarding and alighting can be provided to facilitate and expedite passenger movements (Diaz and Schneck, 2000).

- Bus interior design: The interior design of a bus is one of the most influential vehicle-related factors for the overall capacity of a system. Vehicles with spacious seats and aisles would undoubtedly provide the utmost comfort, but result in higher vehicle purchase and operating costs and lower seating capacity. Typically, in BRT vehicles, large standing/circulation areas around doors are given to provide storage areas for baby carriages, bicycles and wheelchairs. According to Wright (2005), the amount of space dedicated to standing and seated areas should be based on expected passenger flows and trip lengths, especially accounting for peak demand. On the other hand, if BRT lines are heavily loaded, the most efficient design would be to provide fewer and less comfortable seats and maximize standing capacity. This would result in less overcrowding of vehicles during peak hours (Vuchic, 2007). This practice is most common in Latin American BRT systems.

- Floor elevation: The floor height of BRT vehicles can be of three types (Zimmerman and Levinson, 2004): (1) 100% low floor; (2) partial low floor (usually about 70%); and (3) high floor. Low-floor buses are often used to provide easy boarding and alighting for passengers with disabilities, young children, the elderly, expectant mothers, passengers with baby carriages and people carrying heavy loads. It also reduces the boarding and alighting times of passengers; however, the dwell time is increased, due to the time needed to lower and raise the bus. Since these buses are closer to the ground, they typically incur more mechanical stresses and, thus, higher maintenance costs. High-floor buses are often used when absolute maximum carrying capacity is required; however, high-floor buses can substantially increase the boarding and alighting process (Vuchic, 2007). This can be countered by matching the station dock height precisely with the vehicle floor height. According to Diaz and Schneck (2000), the most common strategy to improve speed, reliability and user-friendliness is the matching of the boarding platform height to the vehicle floor height by raising the platform to meet a high-platform bus, such as the BRT systems in Curitiba and Sao Paulo, Brazil, and Quito, Ecuador.

- Vehicle propulsion: Vehicle propulsion systems range from diesel powered buses to more recent alternative fuel applications, such as electric power and fuel cells. Cleaner and quieter operation of BRT vehicles enhances the overall image of the system and results in greater environmental benefits.

- Vehicle form and aesthetics: Vehicles of distinctive design, aesthetic features and color schemes should be used to make the system more inviting and appealing to potential users.

- Wi-Fi: Wi-Fi service can be provided both on-board of BRT vehicles and at BRT stations. It can be provided either free of charge, for a fixed fee or pay per use. Passengers can utilize their commuting/in-vehicle travel time for entertainment or work, which may make their transit travel more enjoyable or productive and, at the same time, decrease their perceived travel time. Wi-Fi is not a critically important element; however, it is an example of a high-quality customer amenity that can promote the BRT image, create additional appeal to the customers and be a significant symbol of BRT brand identity (APTA, 2010).

3.3 Stations

Successful BRT systems are largely dependent on the location, spacing and design of their stations, which serve as the links between the systems and their customers. BRT station characteristics include length, platform height, fare collection practices and amenities provided for passengers (Vuchic, 2007). These may vary from system to system.

Stations can be located on streets, adjacent to busways or expressways or in off-street transit centres that can serve more than one transit route. The station location needs to be coordinated with the adjacent urban development. Moreover, the appearance of the station should be distinctive and consistent with the appearance of the BRT vehicles to promote brand identity. For example, in Curitiba, the stations are tube-shaped, made of glass and steel, allowing them to be transparent and have the capability of accommodating a full busload of passengers.

Consideration should also be given to passengers with reduced mobility by providing a wheelchair lift (Grava, 2003). For the TransJakarta system, the BRT stations are connected to the sidewalk by a pedestrian bridge and ramps to facilitate the movement of wheelchairs (Ernst, 2005). Other passenger amenities may include newspaper boxes, drink and fare vending machines, trash containers, heating, cooling and public telephones. Electronic signs indicating bus arrival times are also very important features. In order to ensure passenger safety and security, both actual and perceived, emergency telephones and alarms should also be provided. In short, BRT stations should provide more comfort and amenities for passengers than standard bus stops.

The following minimum total cost bus stop spacing has been derived by Wirasinghe (2008) for routes with many-to-many demand distributions:

$$S^*(x) = 2\left[\phi(x)\left(\frac{\gamma_r}{\gamma_k}\right)\left(\frac{C(x)}{p(x)}\right) + \frac{n\phi(x)\lambda_B + \lambda_S}{\gamma_k p(x)}\right]^{\frac{1}{2}}$$

where

$S^*(x)$ - the minimum total cost bus stop spacing centered at *x*;

$\phi(x)$ - the time lost due to stopping at *x*, which is independent of the number of boarding and alighting passengers;

$C(x)$ - the cumulative number of passengers per day traveling past *x*;

$p(x)$ - combined passenger demand for boarding and alighting per day per unit length at *x*

λ_B - the owning and operating cost per bus per unit time, which includes crew, maintenance and fuel costs, and the discounted capital cost allocated over operating time periods;

λ_S - the cost of a bus stop per day;

n - the number of bus dispatches per day;

γ_r - the mean value of riding time in $ per unit time per passenger; and,

γ_k - the mean value of walking time in $ per unit time per passenger.

3.4 Operations Control Systems

The use of elements of an intelligent transportation system (ITS) for the control of a BRT system is an important part of BRT operation. The control technologies applied may vary, depending on the operating environment, physical constraints of the city, as well as budget limitations (Diaz and Schneck, 2000). Applications of ITS technologies include automatic vehicle location (AVL) systems, specialized bus signals, signal activation sensors and control systems for providing transit signal priority (TSP) at signalized intersections and mixed roadway rights of way. TSP helps improve bus speeds, facilitates bus turns and reduces waiting times for buses crossing intersections. It has been reported that this TSP works best when separation times between buses are over 4 minutes (Wright, 2005). The use of AVL also helps in conducting follow-up analyses of the collected vehicle data over time, in order to evaluate the overall service performance and to compare the scheduled and actual BRT vehicle running times.

3.5 Fare Collection Systems

The fare collection system is another important component of BRT systems, directly affecting costs, ridership, boarding times and revenues. Fare collection systems have a significant impact on passengers' overall impressions of the system. There are several alternative methods available for fare collection, such as on-board, off-board, payment by cash, prepaid tickets, passes, magnetic strips or smart cards. Each method has different boarding times, capital and operating costs associated with it. The more efficient systems (e.g., contactless smart card) may have higher capital costs.

Among the different options, off-board fare collection is desirable, because it is more convenient for customers. It permits multiple-door and/or all-door boarding, thereby reducing station dwell times and bus operating costs and expediting passenger flows (Levinson et al., 2002). Goodman et al. (2005) reported that, in the case of the Curitiba BRT system, same-level bus boarding combined with preboarding fare payment result in a typical dwell time of no more than 15 to 19 seconds at a stop, although that may increase with higher passenger flows. Tirachini and Hensher (2011) found that off-board fare payment is the most cost-effective system, particularly when the demand is high.

Some on-board fare collection mechanisms, however, can also support multiple-door boarding, but they must be carefully selected. Smart card technology can be applied at multiple doors to help facilitate simultaneous on-board fare payment and multiple-door boarding without increasing revenue shrinkage (Levinson et al., 2002). Smart card data combined with AVL data also provide an accurate and valuable database that can be used to monitor the online and offline performance of a BRT system, including schedule adherence, dwell time, transit origin destination, ridership, passenger transit times and passenger kilometers driven. These data are valuable for ridership analyses and planning and operation of transit systems.

3.6 Passenger Information System

Efficient, accurate and easily accessible passenger information technologies are important to enhancing the overall user-friendliness and attractiveness of the system and riders' perceptions of the quality of service (Rahman et al., 2012b). For example, it has been reported that real-time information, especially the at-stop variable-message displays regarding bus arrival times, significantly influences passengers' decisions to use the BRT service (Rahman, 2011a; Dziekan and Kottenhoff, 2007). Thus, these are critically important characteristics of a BRT system.

Transit information for passengers can take many forms, including information before, during and at the termination of the trip. The main sources of information that need to be provided are route guidance and schedule details that can be accessed via telephone and/or Internet before making a trip to help with trip planning; real-time information of upcoming bus arrivals and service disruption alerts at stations or other points prior to boarding a transit vehicle; periodic location information, time to next stop, next-stop announcements and possible transfer connections during the trip. The provision of real-time at-stop information displays significantly reduce uncertainties in transit arrival times and perceived waiting times at a transit stop (Dziekan and Vermeulen, 2006; Lehtonen and Kulmala, 2002; Nijkamp et al., 1996).

The term BRT refers to the integration of all the above components forming one functional system; however, the mix of elements depends on the local market and attributes, operational and physical environments, and the availability of resources (Hidalgo and Graftieaux, 2008). The options available for the various BRT components are extensive and lead to a large variety of integrated systems so that no two are the same, even within different metropolitan areas of a region (Federal Transit Administration (FTA), 2004).

The performance of BRT system can be described in terms of speed, capacity, reliability, accessibility and safety.

3.7 Speed

The speed of a BRT line is influenced by stop spacing, TSP measures and the design of the rights of way. The spacing of stops has a measurable impact on the BRT system's operating speed and passengers travel time. Since a BRT system concentrates passengers at limited stops, passengers typically travel longer distances than conventional bus passengers. BRT vehicles stop and encounter delays at fewer locations along the route and sustain higher mean travel speeds.

TSP technologies deployed with BRT systems can be used to extend or advance green times or swap left turns to allow buses that are behind schedule to get back on schedule, improving schedule adherence, reliability and speed. The combined presence of an exclusive right of way and TSP for at-grade traffic are the most effective ways to increase bus travel speeds, allowing BRT systems to compete with most heavy rail and exclusive right-of-way light rail systems (TCRP, 2003; FTA, 2004). Dedicated transit ways / busways, limited-stop / express services, and exclusive bus lanes / freeways have become part of BRT systems, significantly enhancing performance. Higher speeds help compensate for the increased amount of time required to walk, take transit or drive to BRT stations.

3.8 Capacity

Transit capacity is defined in terms of either passengers or transit vehicles. Passenger capacity refers to the maximum number of seated and standing passengers (capacity in passengers per hour per direction) that a BRT system can safely and comfortably accommodate. Transit vehicle capacity is expressed as the maximum number of transit vehicles (capacity in vehicles per hour per direction) that can be moved past a point by a BRT system. In practice, the operator of a BRT system attempts to provide capacity for the required passenger demand. However, when passenger demand is not accommodated, many service qualities of the BRT line (e.g., operating speed, comfort and reliability) may be negatively affected. Therefore, ensuring adequate capacity for BRT systems is important.

There are three key elements that determine BRT system capacity: BRT vehicle (passenger) capacity; BRT station (vehicle and passenger) capacity; and, BRT running way (vehicle) capacity. Limitations in any one of these elements constrain the throughput of the total BRT system.

The characteristics of the BRT system running ways and station capacities mainly govern the vehicle capacity. For both running ways and stations, capacity is enhanced by either operating strategies or design elements that increase the speed and capacity of the system. Examples of such design elements imply investment in infrastructure, such as the use of multiple running way lanes, larger vehicles and larger stations. On the other hand, operating strategies that reduce delays and improve the service rate of the system include traffic prioritization systems, access control and strategies to reduce dwell time (FTA, 2004; Thilakaratne et al., 2011).

Capacity is also a function of the desired level of service (LOS) of a BRT system. The parameters affecting LOS include: (1) availability of service (dispatch rate, headway and coverage); (2) level of comfort (standee density); (3) travel time; and, (4) Reliability. An illustration of various concepts of capacity is presented in Figure 3. The dispatch rate of service and the size of the actual vehicles are the main determinants of actual operating capacity.

In general, BRT systems start their operation at a lower frequency or with smaller vehicles than the system can accommodate, as often the initial passenger demand does not require the maximum capacity of the system. As the demand varies during the service span, the frequency and vehicle size are adjusted to meet demand and take advantage of any unused capacity (FTA, 2004; Thilakaratne et al., 2011).

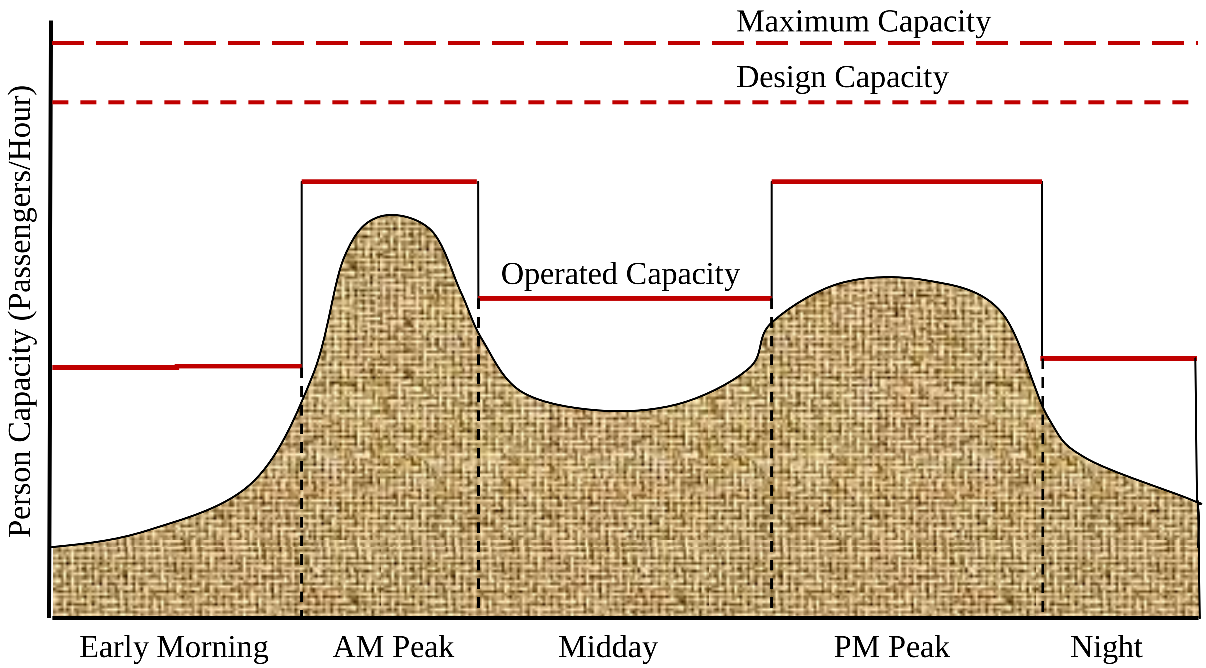

Figure 3. Relationship between aspects of capacity [Source: FTA, 2004]

Table 3. The Best and Most Familiar Closest Fits for capacity and speed of BRT
[Source: Thilakaratne et al., 2011]

Bus Rapid Transit	The Best Fit (Chi-Squared Value)	The Most Familiar Closest Fit (Chi-Squared Value)
Average Observed route capacity	Weibull (0.49)	Normal (1.24)
Average Speed	Burr (0.50)	Beta (1.43)

Standard probability distribution functions of the speed and flow data can be examined (Table 3). For example, the histograms for the average speed and observed route capacity of the BRT are shown in Figures 4 and 5, respectively. The blue and red color functions represent the best and the most familiar probability distributions in terms of closest fits, respectively (Thilakaratne, 2011).

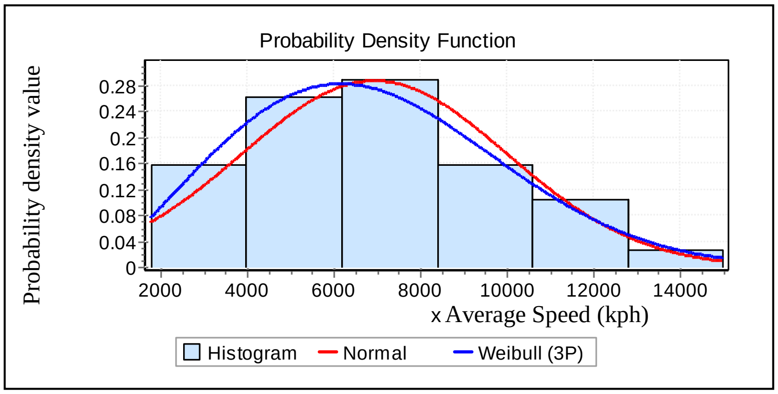

Figure 4. Histogram for the average speed of a BRT system (Source: Thilakaratne, 2011)

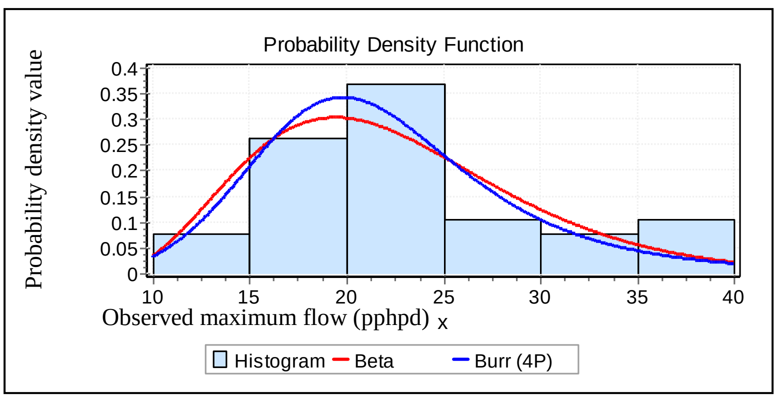

Figure 5. Histogram for the observed route capacity of a BRT system (Source: Thilakaratne, 2011)

The mean and standard deviation of the average speed and average observed maximum directional passenger flow were 18 and 4 (km/h) and 7669 and 4359 (passengers per hour per direction, pphpd), respectively. The wide variations in the speed and line capacity data were due to the significant effects of other factors (discussed in Section 3), which were not considered in this analysis. Figures 6 and 7 illustrate the average speed and observed minimum and maximum capacities of various modes, respectively, in ascending order from regular line (local) bus to metro to compare the relative performance of BRT systems (Thilakaratne et al., 2011). It can be seen that BRT and busways when considered together have performance characteristics similar to LRT, in terms of both speed and capacity.

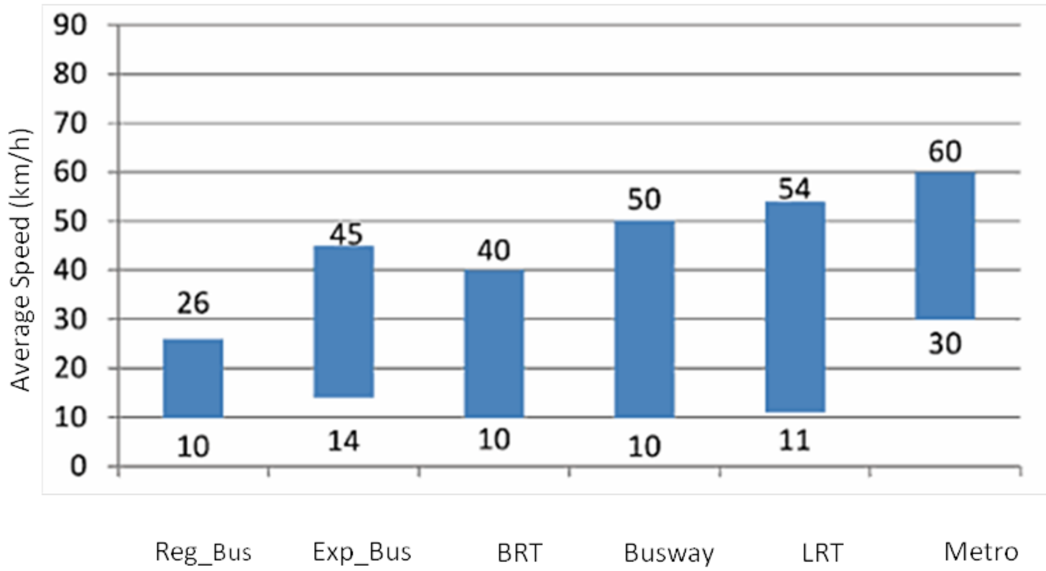

Figure 6. Average speed by mode [Source: Thilakaratne et al., 2011]

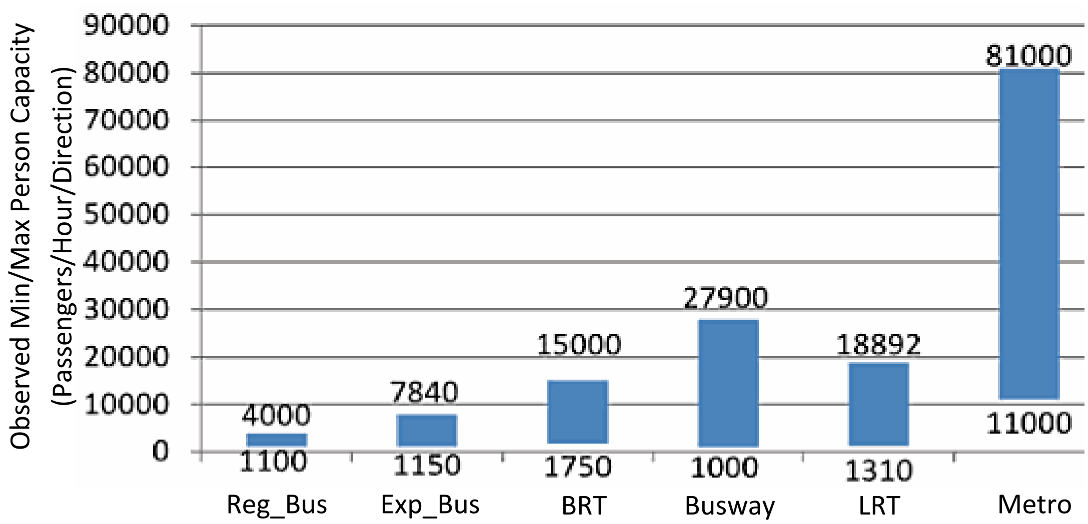

Figure 7. Observed minimum and maximum passenger capacities by mode (Source: Thilakaratne et al., 2011)

3.9 Reliability

Passengers are more likely to use a transit service that is highly reliable. Passengers may switch to other transportation choices if a transit service does not consistently provide the expected levels of service. There are many features that can improve BRT reliability. The three main aspects of reliability are running time reliability (ability to maintain consistent travel times), station dwell time reliability (ability for patrons to board and alight within a set time frame) and service reliability (availability of consistent service) (TCRP, 2003; FTA, 2004). The first two aspects “relate to ability of the system to meet a schedule or a specified travel time consistently, while service reliability captures the characteristics of the system that contribute to passengers perception of service availability and dependability” (FTA, 2004).

In addition to the above factors, there still can be wide variations in overall reliability, since BRT service (like other transit modes) can be affected by external sources of uncertainty, such as traffic conditions, vehicle breakdowns due to unforeseen mechanical or non-mechanical problems, traffic signals, route length, recovery times built into the route schedules, number of stops, evenness of passenger demand, and the frequency of request of the use of wheelchair lifts/ramps if present (Wirasinghe, 1993; Wirasinghe and Liu, 1995a, 1995b; Liu et al., 2003; FTA, 2004; Vuchic, 2007; Rahman et al., 2010; Rahman et al., 2011b).

The reliability of a BRT system can be improved by making some of the stops time-points. In the case of busways, which are similar to LRT systems, each stop can be a time-point. Wirasinghe and Liu (1995a) suggested a dynamic programming method for determining the optimal number of time-points and travel time schedules for the case of high headways when buses can be assumed to be independent of prior buses.

3.10 Accessibility and Safety Improvement

Accessibility to BRT vehicles and circulation within vehicles are governed by several features, which can significant impacts on dwell time, capacity, passenger comfort, and community and rider acceptance of a BRT system (TCRP, 2003; FTA, 2004). These features are seat layout (increases in aisle width within the vehicle increase the standing capacity of the vehicle as well as providing additional space for passenger circulation), additional door channels (facilitate the boarding process by allowing multiple queues of passengers to enter the BRT vehicle at one time), and enhanced wheelchair securement (reduces the amount of time to secure wheelchairs in bus operation) (FTA, 2004).

The level and frequency of accidents and injuries experienced by passengers and employees of the transit system is a measure of safety. Nevertheless, collisions involving buses are a serious safety concern, due to their size and operational and occupancy characteristics (Rahman et al., 2012). The level of safety managed by a transit agency is defined with two performance measures: accident rates (per service hours or service miles) and public perception of safety. The public perception of safety is often measured using passenger surveys or information gathered from customer feedback (FTA, 2004).

In general, BRT systems have high safety and security levels, resulting from high service frequencies that reduce perceived vulnerability at stations, separated rights of way (BRTs run on dedicated lanes) that reduce hazards and conflict with other vehicles, low floors that decrease tripping hazards, electronic fare collection that limits passenger vulnerability during cash transactions and advanced camera technologies that facilitate active management of the BRT system, deterring crime and enabling responses to incidents (FTA, 2004; Vuchic, 2007).

4 Users' Perception and Modal Shift

The ability of BRT to provide high-quality transit service results in high user satisfaction. This increase in transit quality was shown to lead to modal shifts from private vehicle to transit, as identified in several studies conducted in a number of cities in Asia and North and South America (Rabinovitch and Hoehn, 1995; Deng and Nelson, 2010a).

A recent passenger survey from Beijing's Southern Axis BRT Line 1 showed that BRT has gained great popularity among passengers. It was also reported that the majority of passengers are work-related commuters and use BRT more than once a day. Captive users had even higher satisfaction than choice users, in terms of reliability, comfort and cleanliness, and overall satisfaction (Deng and Nelson, 2012a). Another study (Deng and Nelson, 2010a) indicated that BRT was a competitive alternative to private vehicles, especially during the rush hour. Although they had a car alternative for the journey, 12.4% of the passengers still chose to use the BRT system.

Cain et al. (2009) conducted an attitudinal survey of 2400 transit users and non-users in the Los Angeles area to quantify the importance of the image of the BRT system. This survey used a set of factors to categorize the perceived differences among BRT, LRT and metro. It was revealed that the public had a good perception of the BRT service. The Orange Line (BRT) attained ratings akin to the Gold Line (LRT), in terms of both tangible and intangible factors. From the survey results, it was concluded that a BRT system could compete with an LRT system, at least based on public perception. A survey conducted by Callaghan and Vincent (2007) found that the Orange Line successfully attracted choice users, with 18% of riders switching from private car to BRT. Although more than a third of passengers had a car available for their trip, 79% of passengers accessed the BRT stations by transit rather than car.

A survey of commuters traveling on New Delhi's BRT corridor was conducted by the Centre for Science and Environment, Delhi Greens and the Indian Youth Climate Network (2008). It was found that 83% of commuters were pleased with the dedicated BRT lanes and believed that the BRT system should continue operating. If the BRT system had an extensive network and connected with the metro, 26% of car and two-wheeler commuters were willing to shift from their current transport mode to BRT. It has been argued that Janmarg, India's first advanced-featured BRT service with median stations, level boarding and central control, which opened in Ahmedabad in 2009, had the potential to help revive the image of public transport in India (Institute for Transportation and Development Policy, 2009).

A user survey piloted in Dartford and Gravesham, UK, by Fastrack Delivery Executive (2006) revealed that 19% of passengers previously using a car shifted to the BRT system; and, 95% of customers graded the overall Fastrack experience as excellent or good. This system achieved a high level of customer satisfaction with travel demand 50% above forecasted levels.

Another survey in Curitiba, Brazil, indicated that 25% of the commuters who previously used a private car had switched to the BRT system, although it has one of the highest car ownership rates in Brazil (Rabinovitch and Hoehn, 1995).

The U.S. Federal Transit Administration (2004) reported that there have been significant increases in transit ridership in virtually all of the corridors where BRT has been implemented:

ridership gains of between 5 and 25% were common. The significantly higher gain of 85% on Boston's Silver Line represents the potential for BRT systems.

5 Social, Environmental and Economic Impacts of BRT

BRT systems are often associated with positive environmental, social and economic benefits. BRT is shown to have a powerful influence in attracting new economic development and sustainable growth along its corridor and around its stations (Munoz-Raskin, 2010; Rodríguez and Mojica, 2009; Rodríguez and Targa, 2004; Cervero and Kang, 2011). BRT stations often facilitate transit-oriented development (TOD) with increased residential and business densities (Currie, 2006a), a diversity of land uses and, thus, shorter distances to trip destinations. TOD results in improved accessibility to employment and other service opportunities.

As discussed in Section 4, the improved comfort, convenience and travel time savings of BRT, compared to regular bus service, may induce a modal shift from private car to a BRT system, leading to short- and medium-term traffic reduction along the BRT corridor, which in turn leads to reduced air pollution and lower greenhouse gas emissions. The likely reduction in vehicular traffic also results in improved road safety.

Wright (2007) reported that, when measured in terms of economic, environmental and social benefits, BRT's track record provides a compelling case for more cities to consider BRT as a transit priority. Table 4 outlines some of the direct benefits that BRT has provided to developing cities.

Most of the existing literature on the assessment of the impact of BRT has been focused on developing countries, with few findings related to developed countries. In the following subsections, some of the findings regarding environmental, economic and social benefits of BRT are examined. These impacts are shown to differ from one city to another, depending on the network characteristics, congestion levels, BRT characteristics and the modal shares before and after the implementation of a BRT system.

5.1 Environmental Impacts

Like other successful transit services, BRT has a major role to play in reducing the impact of air pollution from transportation sources. The factors contributing to these improvements are mainly the decrease in the number of vehicles in the BRT corridor, resulting from a shift in modal share from auto users to BRT and the selection of alternative fuels, propulsion systems and pollutant emission controls that are usually used by BRT systems (Federal Transit Administration, 2004). In addition, transit agencies may serve passengers with fewer hours of vehicle operation, potentially reducing emissions.

The level of reported improvements depend on many factors, such as the resulting percentages of modal shift, traffic improvement, travel time savings for both transit users and general traffic, the type of transit vehicle used for BRT operation, and the extent of reductions in time exposure to pollution.

Vincent et al. (2012) reviewed the environmental benefits of the BRT systems in México City, México, Guangzhou, China, and Bogotá, Colombia. They showed a 61.8% reduction in CO_2 and a 50% reduction in diesel consumption compared with operation prior to the implementation of a BRT system. In Bogotá, Echeverry et al. (2004) reported a drop in particulate matter pollution in some parts of the city by up to 9%.

Table 4. Benefits of BRT [Source: *Wright, 2007]*

Benefits	Description
Economic	➢ Reduced travel times ➢ More reliable product deliveries ➢ Increased economic productivity ➢ Increased employment ➢ Improved work conditions
Social	➢ More equitable access throughout the city ➢ Reduced accidents and illness ➢ Increased civic pride and sense of community
Environmental	➢ Reduced emissions of pollutants related to human health (i.e. CO, SOx, NOx, particulates, CO_2) ➢ Reduced noise levels
Urban form	➢ More sustainable urban form, including densification of major corridors ➢ Reduced cost of delivering services, such as electricity, sanitation, and water
Political	➢ Delivery of mass transit system within one political term ➢ Delivery of high-quality resource that will produce positive results for virtually all voting groups

Wöhrnschimmel et al. 2008, analyzed commuters' exposure to carbon monoxide (CO), particulate matter (PM) and benzene. Data was collected both before and after the implementation of a BRT system along a 20-kilometer corridor in Mexico. The pollutants were measured inside the buses and mini buses during the morning commute. The results showed a significant reduction of CO (25-45%), benzene (54-69%), and PM2.5 (20-30%). It was also suggested that the resulting lower commuting times further reduced total commuters' exposures to the pollutants. However, no significant reduction in PM10 exposure was observed.

Nugroho et al. (2011) estimated the impact of BRT on the concentration of secondary pollutants in the roadside areas near transit corridors in Jakarta, Indonesia. The analysis was based on field data collected at five continuous ambient air quality monitoring stations located near TransJakarta BRT corridors in 2005. The introduction of the BRT system and the modal shift it produced were shown to have a greater influence on rapidly decaying pollutants, such as PM10, than on ozone. However, no clear improvement in the ozone concentration could be attributed to the BRT system.

A North American study that examined the environmental impact of BRT was conducted by

Vincent and Callaghan (2006). It focused on estimating the potential reduction in CO_2 that would result from a BRT system for commute trips in a typical North American city. Three scenarios were analyzed: a no-build scenario; an LRT scenario; and, a BRT system using 40- or 60-ft low-emission buses. The findings highlighted the potential of BRT in providing significant reduction in greenhouse gases with 40-ft compressed natural gas (CNG) buses.

5.2 Economic Impacts

One of the significant benefits of BRT is its positive long-term influence on TOD (transit-oriented development) and mixed-use and high-density land development policies (Currie, 2006a). Such development policies, if properly supported with transportation policies, result in changes in the location decisions of residences and firms, resulting in increased land values and improved accessibility to employment and other opportunities. BRT implementation has been shown to result in positive property development impacts in Bogotá, Columbia (Munoz-Raskin, 2010; Rodríguez and Mojica, 2009; Rodríguez and Targa, 2004) and Seoul, Korea (Cervero and Kang, 2011). Similarly, experiences from cities that adopted BRT, such as Boston, Pittsburgh, Ottawa and Vancouver, show that there have been significant positive development effects in locations where there was investment in transit infrastructure (FTA, 2004).However, it is likely that LRT and metro systems also have similar benefits.

5.2.1 Change in Densities, Land Use and Location Decisions

It is argued that modern BRT systems can increase density around transit nodes and, thus, lead to TOD (Currie, 2006a; TCRP, 2003; Cervero and Kang, 2011). Vincent and Callaghan (2008) also examined TOD projects in York Region, Ontario, and El Monte, California, and concluded that the type and level of investment occurring near BRT stations was comparable to that of TOD near rail transit.

Kang (2010) confirmed that BRT is associated with the location of creative industries and service sectors within 500 meters of bus stops in Seoul, Korea. The BRT operation was shown to increase the employment density in the vicinity of stations by up to 54%.

Deng and Nelson (2012b) conducted a survey to evaluate the impact of the Beijing Southern Axis BRT system. The results showed that a large majority of respondents (46.1%) had moved to a location near a BRT station after full operation of Line 1 began in December 2005. In addition, 49.5% of non-locally resident respondents showed interest in residential properties along the BRT corridor. In Latin American cities, the increased likelihood of living close to BRT stops was shown to be associated with a decrease in auto ownership and use (Zegras, 2010).

5.2.2 Land Values

The improved accessibility to land in the proximity of BRT stations is reported to have a positive impact on property values. Many residential projects, specifically high-density apartments, were built after the implementation of the BRT system in Beijing. Deng and Nelson (2012b) quantified the impact of BRT Line 1 in Beijing on the value of residential apartments in a series of catchment and control areas. They found that the average price of apartments adjacent to a BRT station had a relatively faster increase than those not served by the BRT system.

Similarly, positive property development impacts resulting from BRT implementation have been identified in Bogotá, Columbia (Munoz-Raskin, 2010; Rodríguez and Mojica, 2009; Rodríguez and Targa, 2004), Seoul, Korea (Cervero and Kang, 2011) and in the U.S,. Canada and Australia (Vincent and Callaghan, 2008). According to the analysis of a survey of developers conducted in Brisbane, Cleveland, Boston and Ottawa, roughly half of the participants indicated that proximity to BRT increased property value by a minimum of 3-5%, compared with similar properties not in proximity to BRT (Vincent and Callaghan, 2008).

5.2.3 Mobility Benefits

BRT has been shown to lead to significant travel time savings and improved travel reliability for transit vehicles, resulting in higher quality service and a high modal shift from private cars. These improvements are significant, although their level has been found to vary greatly.

Vincent et al. (2012) stated that the Brisbane Southeast BRT system has reduced overall travel times by up to 70%. Echeverry et al. (2004) reported that the Bogotá BRT system was responsible for a 32% reduction in travel time for BRT users. The Metrobús BRT system in Mexico City was reported to result in travel time savings of 40% (Molina, 2010). Callaghan and Vincent (2007) indicated that, since the opening of the Orange Line in Los Angeles, the southbound traffic flow had improved at around 7% during the morning peak time, and the northbound traffic flow in the evening rush hour had improved by 6%. With the opening of a BRT system in Toulouse, France, the average traffic speed increased by 3% between 2007 and 2008 (Rabuel, 2010). However, it is questionable as to whether these improvements will last.

Most importantly, the reliability of travel time has also been shown to improve significantly. While previous transit riders had a 25% chance of being 7 minutes late or more and a 5% chance of being 30 minutes late or more, riders of the new BRT system in Mexico were found to be 5 minutes late or more less than 5% of the time (Molina, 2010).

Tiwari and Jain (2012) stated that the time savings were not consistent among the different groups of travelers on the New Delhi BRT corridor. They varied for different transport modes and depended on the distance traveled. They reported a 33.33% reduction in travel time for bus users. Surprisingly, since the number of private vehicles along the corridor also increased, the author reported a 14% increase in travel time for private autos. However, by weighting the vehicles by occupancy, they reported an overall total travel time saving of 19.7% for the entire corridor for all users.

5.3 Social Impacts

5.3.1 Safety Benefits

A BRT system can also result in traffic safety improvements, which are attributable to the reduced number of private vehicles resulting from the high modal shift to BRT and to the use of exclusive lanes for buses, which reduce conflicts between buses and other vehicles. However, the range of improvements can vary greatly. For instance, while the Bogotá BRT system has been reported to result in a decrease in accident rates along the route by 90% (Echeverry et al., 2004), the Mexico BRT corridor has reduced collisions by up to 20% (Molina, 2010).

Tiwari and Dain (2012) compared the safety improvements for different modes of transportation after the implementation of the New Delhi BRT corridor. The analysis showed that safety of pedestrians who were affected by the bus operation improved.

5.3.2 Improved Accessibility to Employment and Other Opportunities

The BRT benefits of shorter travel times, improved mobility and more choices of transportation modes are also indicators of improved accessibility to employment and other service opportunities. Tiwari and Jain (2012) quantified the improved accessibility options to opportunities to be 120% for cyclists and 730% for people who walk to access buses on the New Delhi BRT corridor.

5.3.3 Equity

The implementation of a BRT system results in improved social equity, due to its direct and indirect benefits to a wide spectrum of users. Transit users benefit from improved service and travel times, which result in a high shift from private vehicles to BRT.

In Bogotá, since bus users tend to be more socially disadvantaged, the BRT system was expected to bring more direct mobility and accessibility benefits to this particular group of passengers. While some findings in the literature supported this hypothesis, other findings did not. According to Cain (2006), a good equity outcome was achieved in Bogotá, due to the reduction in the average transit travel times. These mobility benefits were mainly attributed to the less privileged group who tend to live at the edges of the city.

Accessibility benefits for less privileged passengers, however, were not supported in a recent study conducted for the newly implemented BRT system in Cali, Colombia (Delmelle and Casas, 2012). In this study, accessibility was examined in terms of both access to the transit system itself and access to three activities – health care, education and recreation – around the city and in relation to neighborhood socioeconomic strata. The results indicated that around 80% of the total population was within a 15-minute walk of the BRT system. However, walking access to the BRT system was found to be greatest for middle-income groups and was rather limited for neighborhoods with the highest and lowest socioeconomic strata. The accessibility to activities by BRT was shown to be largely limited to the spatial distribution pattern of the activities. For instance, recreation facilities had the most equitable accessibility as a result of BRT, due to their dispersed locations; however, hospitals had the least equitable accessibility due to their spatially clustered locations.

5.4 Health

Although no studies have been reported on the impact of BRT on health, BRT's capability of generating shorter destinations and walkable cityscape designs is expected to result in a higher percentage of active modes, such as biking and walking, thereby encouraging more healthy lifestyles, as with LRT and metro systems.

In the short term, the high quality of transit service offered by a BRT system may encourage a high modal shift towards transit, resulting in decreased traffic congestion and, thus, significant social, economic and environmental benefits. However, as indicated in the New Delhi study of

Tiwari and Dain (2012), these short-term benefits can be offset over the longer run by the demand induced from the additional BRT-generated improvements. Although this finding has not been supported by other studies, if BRT deployment is not properly supported with transport and travel demand policies, the resulting decreased travel time for private vehicles that is realized through BRT deployment may make travel more appealing, which consequently leads to an increase in private vehicle travel demand. This induced auto demand results in a transportation system with even more vehicles, creating more congestion, energy use and emissions. Thus, BRT development policies must be supported with transportation demand management policies, such as parking management and high-occupancy vehicle (HOV) lanes, suggesting the need for integrating strategies for both sustainable transportation system performance and energy use.

6 Costs and Benefits

BRT systems need a relatively low capital investment per kilometer compared with other mass transit systems (Federal Transit Administration, 2004). Levinson et al. (2003a) showed that BRT is a cost-effective way of providing high-quality transit service with significant user and operator benefits. This relative cost-effectiveness has made BRT an attractive and affordable transit alternative, especially for budget-constrained cities that cannot afford rail transit.

It has been reported that overall capital and operational costs of BRT systems are typically less than those of an LRT system, although ridership and operating speeds can be, in some cases, comparable between BRT and LRT systems (Deng and Nelson, 2011). In the construction of a similar route, a BRT system typically costs 4 to 20 times less than an LRT system and 10 to 100 times less than a metro system.

In another study, Menckhoff (2005) indicated that investment cost for BRT is often less than one-tenth per kilometer than other mass rapid transit alternatives. In other words, with the same budget, BRT may be able to deliver greater network coverage than rail systems. Hossain (2006) showed that BRT could cost US$1.3 million per kilometer, whereas the cost for the metro of Bangkok's mass transit project was US$43.4 million per kilometer. Table 5 shows a comparison of capital and operating costs for different mass transit systems.

Table 5. Costs of different mass transit systems [Source: Deng and Nelson, 2011]

	Bus Rapid Transit	**Light Rail Transit**	**Metro**
Average Capital Cost (2000 US$/mile in millions)	13.46	34.70	168.51
Average Operating Cost (2000 US$ / vehicle revenue mile in millions)	4.73	12.22	8.54

Although the exact capital cost depends greatly on local circumstances, 20 existing BRT lines were reviewed by the U.S. Government Accountability Office (2001), finding that BRT was a cost-effective solution. In another study, Hidalgo and Graftieaux (2008) observed that the capital costs of 11 selected BRT systems in Latin American and Asian cities varied from US$1.35 million per kilometer to US$8.2 million per kilometer. Figure 8 shows the summary of infrastructure costs associated with the implementation of BRT systems around the world, as illustrated by Hensher and Golob (2008).

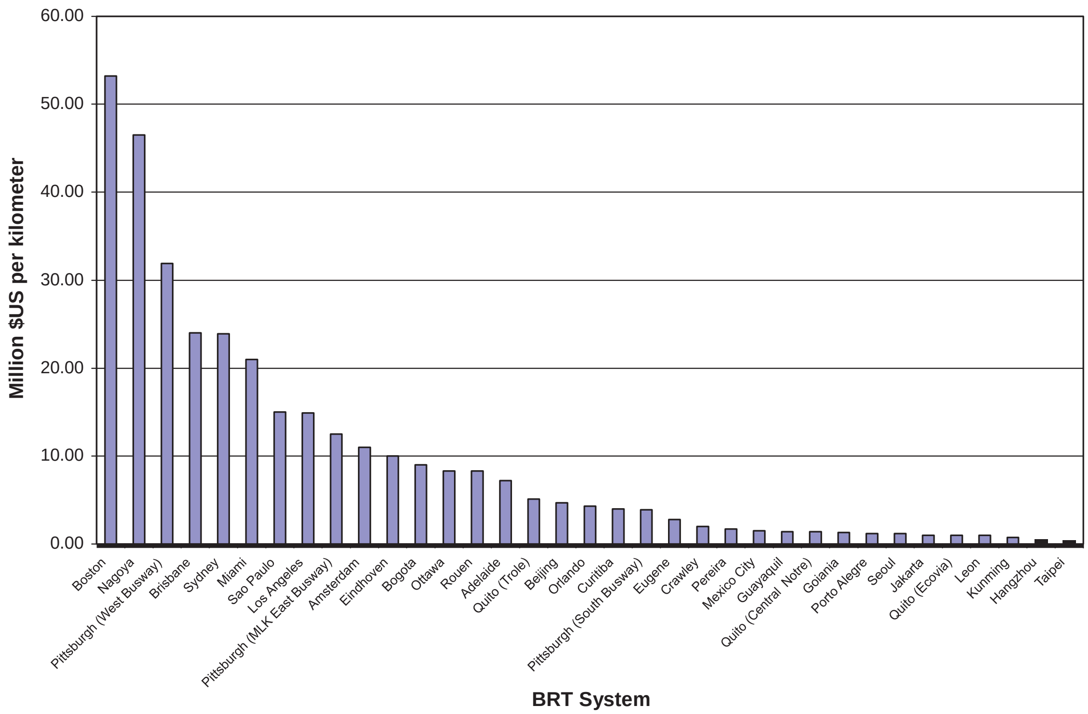

Figure 8. Total infrastructure costs per kilometer (2006 US$ million) [Source: Hensher and Golob, 2008]

The infrastructure costs shown in Figure 8 vary greatly, from a high of $53.2m per kilometer in Boston to a low of $0.35m per kilometer in Taipei. This wide range of costs reflects the local system development as related to the costs of materials, labor and land acquisition, as well as the different years in which the systems were built. The costs also depend on individual features, such as station design, degree of separation from traffic, and technological features. Hensher and Golob (2008) identified the most influential design elements that are systematically linked to higher costs of infrastructure: (1) the number of terminals; (2) the number of intersections with priority signal control; and, (3) the number of grade separations.

In the same survey, Hensher and Golob (2008) indicated clearly that such univariate comparisons are rather limiting and must be interpreted in the context of input cost differences across nations. They also observed that the variation does not systematically vary by country or continent, given an initial expectation that input costs may be greater in developed economies. For instance, the seventh most expensive BRT was in Sao Paulo, Brazil, with the 12th most costly in Bogotá, Columbia, both of which are in Latin America.

The most tangible benefits of BRT are additional ridership, cost-effectiveness and operating efficiencies; however, increases in transit-oriented land development and environmental quality are also closely linked to the implementation of BRT systems (Federal Transit Administration, 2004). Furthermore, travel time savings and higher reliability enable transit agencies to operate more vehicle miles of service for each vehicle hour operated.

Beyond the previously discussed positive impacts of BRT, there exist multiplier impacts that can further increase the value of a BRT system to a municipality. As with other mass transit systems, BRT can reduce public costs associated with vehicle emissions and accidents. Such impacts may include costs borne by the health care system, police force and judicial system. By decreasing these costs, municipal resources can be used in other important areas, such as preventative health care, education and nutrition (Wright, 2007).

7 Planning Aspects & Optimality

The design of a new BRT system affects the operational, physical and environmental settings of the surroundings it will serve. BRT planning may lead to significant improvement in service aspects, such as frequency, directness, understandability, comfort, reliability, operational efficiency and, above all, rapid service. New BRT systems may vary in different corridors, cities and regions, depending on the available capital and operating budgets, passenger demand, available rights of way and potential route configurations (FTA, 2004; Thilakaratne, 2011). The following subsections detail some of the basic planning aspects and optimality in providing a new BRT system.

7.1 Route Length

The route length affects the destinations the passengers can directly access with or without transferring. Route length is also an important input for the assessment of resources required to serve the route. Longer routes may minimize the need for transfers, but may require more capital investment and labor resources and result in higher variability in operation. Although shorter routes may require passengers to transfer to reach locations not served by the route, they generally provide higher travel time reliability (FTA, 2004; Hensher, 2008; Thilakaratne, 2011).

BRT route length has been considered in detail in Thilakaratne (2011) with the determination of the optimal length of a public transit corridor when the local bus system evolves to become an express bus system at a minimal cost. He found the optimal BRT stops, given that local buses stop at all stops, and determined the frequency of service, so as to minimize the costs to the bus system as well as the time costs to passengers.

7.2 Route Structure

Various vehicle types and sizes can be accommodated on a BRT system, based on the route patterns and structures. Simple route structures with just one or two routes are easy for new passengers to understand and navigate. Clarity and choice are two key principles to be highlighted when determining the route structure. There are three types of BRT route structure options to be considered (FTA, 2004):

- A single route is the simplest BRT service, with only one type of service for the corridors serving several activity centres and attracting passengers at stations all along the route. This has been further analyzed by Wirasinghe at el. (2011) in the route layout analysis for express buses.

- An overlapping route with skip stop or express variations encompasses various transit services, including the base BRT service for passengers traveling between particular origin-destination pairs, but with a number of routes that may create crowding at stations and result in confusion for infrequent riders.

- An integrated or network system may include local buses, express buses and combined line-haul / feeders (e.g., BRT network in Calgary)

7.3 Service Span

The period of time that a service is available for use is defined as the service span. Service span may be considered where both local bus and BRT systems operate in the same corridor to give passengers a choice between the two services. There are two service span options for BRT service (FTA, 2004): (1) all-day BRT service; and, (2) peak hour only service.

7.4 Service Frequency

Service frequency is one of the most important elements in planning and operating a BRT system. It determines how long passengers must wait for BRT service. Rapid transit systems generally provide high-frequency service, especially in the morning/evening peak hours. The optimal service frequencies of combined local bus / BRT systems affect the service regularity and the ability of peak hour passengers to rely on the BRT service, which can increase revenue. There are two methods of schedule control (FTA, 2004):

- Schedule-based control dictates that operators must arrive within a certain scheduled time at specific locations along the route. Dispatchers monitor vehicle locations for schedule adherence and facilitate connections with other services when schedules are coordinated to match.

- Headway-based control focuses on maintaining headways rather than meeting specific schedules. Dispatchers monitor vehicle locations and issue directions to regulate headways and capacity (traveling with maximum speed, minimizing wait times and vehicle bunching), but do not indicate a specified time of arrival at the end of the route.

Wirasinghe (1990) examined this situation with many-to-many time-varing demand on a bus route, re-examining Newell's dispatching policy on how the optimal frequency can be estimated to minimize the cost of dispatching plus the cost of waiting time, using analytical methods. He allowed the maximum load point to be varied from bus to bus.

7.5 Station Spacing

BRT stations are typically spaced farther apart than conventional stops that serve the local bus service. From an economic point of view, optimal stop spacing of a combined local bus / BRT system greatly influences passengers' access time cost, station cost, travel time cost and transfer costs (Wirasinghe et al., 1981; Wirasinghe, 2011).

7.6 Cost Effectiveness

As discussed in Section 6, BRT capital costs generally range from low to moderate relative to rail systems. BRT systems that operate in mixed traffic have relatively low capital costs per unit distance, while BRT systems operating on dedicated lanes (busways) require moderate capital costs per unit distance (FTA, 2004; Vuchic, 2007).

7.7 Operating Cost Efficiency

BRT systems result in operating efficiency and service productivity for the effective deployment of resources in serving transit passengers. Experience shows that corridor performance indicators (e.g., passengers per revenue hour, subsidy per passenger mile and subsidy per passenger) improve, when BRT operates in corridors where passengers have the option to switch to a BRT system. It enables economic productivity resulting from travel time savings and higher reliability for the optimality of combined transit operation (FTA, 2004).

7.8 Ridership

Generally, corridors where BRT has been implemented are associated with significant increases in transit ridership (Thilakaratne, 2011). The ridership level is a clear indicator of the image of the transit system. The BRT demand increases with existing transit passengers switching from parallel public transit mode(s) on other routes/corridors and by attracting new transit users who previously used private vehicles.

7.9 Environmental Quality

Environmental quality is an indicator of the regional quality of life, supporting public health and well-being and the attractiveness and sustainability of the urban and natural environment (FTA, 2004). Transit operators provide passengers with fewer hours (mostly in the morning and evening peak times) of BRT operation (environmental impact per unit time) and with higher ridership (environmental impact per passenger), in order to potentially reduce the emissions of pollutants per passenger per unit time (FTA, 2004; Vuchic, 2007).

8 Barriers to BRT

Although there is evidence around the world that BRT is a sustainable strategy for improving travel conditions, some challenges are inevitably encountered with the implementation of a BRT system. These challenges may be of political, technical, operational and/or institutional nature

(Weinstock et al., 2011). Wright (2007) summarized several barriers that have prevented wider utilization of BRT systems, especially for developing countries:

- Political will
- Existing operators
- Institutional biases
- Lack of information
- Institutional capacity
- Technical capacity
- Financing
- Geographical/physical limitations

For developed and car-oriented cities, Weinstock et al. (2011) reported that, by far, the most important reason for not implementing BRT is that these cities have much fewer transit riders and far more private car owners than most of the cities that have successfully implemented good BRT systems. Weinstock et al. (2011) also reported that there are political obstacles, which include lack of awareness, politicians' lack of control over transit systems, presence of a less politically powerful, transit-riding constituency, and lack of a corporate lobby in support of BRT. In many cases, local motorists are more empowered in developed countries and able to oppose changes proposed by the government, and this provides another obstacle to BRT development.

Political will is one of the most important challenges facing BRT. As mentioned by Wright (2007), lobby groups from rail and automobile interests may devise a powerful political argument against BRT implementation. Although automobiles may represent less than 15% of the modal share in developing cities, the owners of such vehicles signify the most influential sociopolitical grouping. The idea of prioritizing road space to public transport may seem to counter the benefits of such owners (Wright, 2007).

Administrative and institutional barriers to BRT development have been observed in many countries; and, in several cases, even traffic engineers were found to be initially resistant to change (Wright, 2007). However, in many cases, powerful politicians backed by leading international engineers managed to overrule local engineers' resistance.

In spite of the advances in the accessibility of global information, a lack of knowledge about the concept of BRT remains a very real barrier (Wright, 2007). However, it has been reported that financing is usually less of a problem with BRT than with other transit options. In some cases, local conditions, such as geographical and topographical factors, can create barriers to the implementation of a BRT system. For example, narrow roadways and steep hills can present design challenges. However, in general, there are technical solutions for each of these issues (Wright, 2007).

The New Delhi BRT project has been criticized by media since its first trial run, due to poor design and lack of coordination with different stakeholders (Pucher et al., 2005). Overcrowding, especially in the dense cities, can also pose some challenges for the planning and implementation of BRT systems (Gilbert, 2008). For instance, extreme crowding problems often occur on TransMilenio in Bogotá, which has caused passenger dissatisfaction with the service.

According to the Federal Transit Administration (2004), the most significant physical challenge in planning BRT is the availability of right of way, whether on an arterial roadway, adjacent to a highway, or on a separate right of way. Similarly, the availability of physical property for stations is another key factor in station location. These two factors always impose tension among the different groups involved in planning a BRT system (Federal Transit Administration, 2004).

9 Conclusion

Similar to other higher order transit systems, such as LRT and metro networks, BRT has demonstrated an ability to increase transit ridership within defined corridors. The attractiveness of a BRT system is that it can achieve these advantages with relatively lower investment and community disruption than systems that require more significant infrastructure, such as LRT and metro systems. Local land use policies that support high-density developments, improved BRT accessibility and mobility attract potential developments around BRT stations and along its corridor.

On the other hand, a BRT system can bring changes in two opposing directions by shaping the spatial distribution of land use within a metropolitan area. The impacts of a BRT system on the reinforcement of decentralization and on increasing land values are well reported in the literature; however, the impact of the additional mobility and accessibility to decentralized areas that a BRT system can offer have still not been examined in the literature. By linking affordable residence locations in suburbs to high-density development in centralized urban areas, BRT may encourage further decentralization in the form of growing urban sprawl.

Integrated growth management, travel demand management and land use policies may offer solutions to these challenges and achieve sustainable transportation system performance.

The short history of public bus transport, as described in Section 2, shows that transit operators have since the 1930s attempted to organize the design elements of bus systems to improve customer service, capacity, speed and reliability. It was only in the 1970s that the elements of a rapid bus service were described as Bus Rapid Transit or BRT. Today there are at least 150 BRT systems around the world carrying approximately 25 million passengers per day on over 3700 kilometres of right of way.

The uniqueness of each BRT systems comes from how the basic design elements are organized to achieve the desired functional outcomes. Section 3 provides an overview of the elements of BRT systems; the running ways, vehicles, stations, operational control systems, fare collection systems and passenger information systems. Sections 3 and 7 also describe how the organization of these elements allows BRT services to achieve the speed, capacity, reliability, accessibility and operational safety characteristics that distinguishes BRT systems from regular express bus services.

Section 4 reports on a number of studies which document very positive customer perceptions of BRT service and successes in attracting significant numbers of new customers to BRT.

Section 5 documents the positive social, environmental and economic benefits of BRT systems.

One of the very attractive aspects of BRT is described in Section 6, wherein the relatively low capital cost to implement is recognized. Although there is a wide range in capital costs per kilometre of running way, it is generally recognized that BRT systems cost significantly less than rail based systems. The relative spread in per passenger operating costs may be less given system capacity and operating cost differences around the world.

Although BRT systems now operate throughout the world and have achieved significant success in customer satisfaction and ridership gains in many cities there are still barriers to implementation. Many aspects of BRT are still poorly understood by political and institutional decision makers which may lead to suboptimal transit corridor development decisions. Only through a more through understanding of transit corridor requirements and the elements of a Bus Rapid Transit system will better decisions be made.

The review of Bus Rapid Transit clearly indicates that it achieves many of the general advantages of all higher order transit systems, but also has many unique characteristics that set it apart for consideration.

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