Frequency and Connectivity

Key Drivers of Reform in Urban Public Transport Provision

David HENSHER

Abstract

The selection of appropriate public transport investments that will maximize the likelihood of delivering the levels of service required to provide a serious alternative to the automobile is high on the agendas of many metropolitan governments. Mindful of budget constraints, it is crucial to ensure that such investments offer the greatest value for money. This paper promotes the view that integrated multi-modal systems that provide frequency and connectivity in a network-based framework offer the best way forward. A mix of public transport investments with buses as feeder services and bus rapid transit (BRT) as trunk services can offer a greater coverage and frequency than traditional forms of rail, even at capacity levels often claimed the domain of rail.

Introduction

Cities continue to grow for a whole host of reasons, resulting in levels of traffic congestion that have rarely been observed in the past. The "predict and provide" approach, so common with urban transport planning, typically recommends more road building. This, however, does not contribute in the long term to delivering sustainable city performance that is close to economic efficiency and distributive justice objectives. There are many other ways of supporting these objectives, one of which is improved public transport. This paper takes a strategic look at what are sensible ways to embody improved public transport into the complex workings of a city.

Public transport investment is being touted as a key springboard for a sustainable future, especially in large metropolitan areas with growing populations. Public transport, however, is very much multi-modal and should not be seen as a single mode solution as is so often the case with many ideologues. Hence, any commitment to improve public transport has a growing number of options to pursue. Enhancement in rail systems typically loom dominant in many strategic statements on urban reform (Sislak 2000; Edwards and Mackett 1996), ranging from heavy rail to metro rail and light rail. However there is a growing interest worldwide in making better use of the bus as a primary means of public transport, and not limited as a service that feeds a rail network (Hensher 1999, 2007; Canadian Urban Transit Association 2004; Callaghan and Vincent 2007).

In establishing a role for public transport, it should be enshrined in the motto of delivering "frequency, connectivity and visibility" that is value for money in terms of net social benefit per dollar outlaid. Connectivity refers to the provision of door-to-door services with minimum delay and almost seamless interchanges. Visibility is predominantly knowing where the mode is coming from and going to, and when.

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There are many ways in which bus transport can be developed as part of an integrated network-based public transport system (Hensher 2007a). The BRT systems in South America such as that in Curitiba, Brazil and TransMilenio in Bogota, Colombia (Menckhoff 2005) are good examples. BRT is "...a high quality bus-based transit system that delivers fast, comfortable, and cost-effective urban mobility through the provision of segregated right-of-way infrastructure, rapid and frequent operations, and excellent marketing and customer service. BRT essentially emulates the performance and amenity characteristics of a modern rail-based transit system but at a fraction of the cost. A BRT system will typically cost 4 to 20 times less than a light rail transit (LRT) system and 10 to100 times less than a metro system." (Wright and Hook 2007)

The Appeal of Bus Rapid Transit Systems

Achieving connectivity and value for money

Recent research by Callaghan and Vincent (2007) shows the appeal of BRT when comparing the Orange Line BRT in Los Angeles with the Gold Line LRT in Pasadena, California, both of which connect to the Red Line subway and have similar service patterns and length. The BRT is performing considerably better than the LRT. The latter costs considerably more and carries fewer riders. Capital costs per average weekday boarding for the BRT is US$16,722 in contrast to US$45,762 for the LRT; cost per revenue service hour for BRT and LRT are respectively US$243.18 and US$552.54; and cost per passenger mile are respectively US$0.54 and US$1.08. These are impressive evidence that a BRT system offers better value for money than an LRT system. Metro and heavy rail would be even more unattractive within the service capacity range studied.

Cain et al. (2007) review the lessons that can be learnt from the most successful BRT system—the TransMilenio—in Bogota, Columbia, and its applicability to the United States. The most important findings relate to connectivity and network integrity, reinforcing the view that it is all about networks and not corridors per se. They suggest that BRT is capable of playing a role in the achievement of a wide set of objectives such as sustainable accessibility and urban renewal when implemented as part of a holistic package of integrated strategies. Importantly, it is the commitment to a *network* of BRT routes (and not a corridor view of planning per se) which provides the opportunity to enhance the accessibility and urban renewal benefits from corridor level to metropolitan-wide level. The relatively low capital costs have made a network of BRT routes possible within a relatively short time frame (often within 5 years), with examples such as Brisbane, Philadelphia and Bogota (Hensher and Golob 2008).

BRT, as a high capacity public transport solution for major corridors, forms the centrepiece for a fully integrated network of bus-based services. The connectivity deep into the network's outer fringes is established through a hierarchy of feeder and trunk routes, with almost seamless transfer points. While it is true that this can allow for light rail and heavy rail, the hourly capacity needs in many jurisdictions are such that rail is unnecessary given it higher capital costs (and lower value for money) and greater lifecycle maintenance and operating costs. The fully integrated and connected bus hierarchy can be modified for little cost as markets change, making it very adaptable to the preservation of connectivity relevant to patronage throughout the network.

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Increasing capacity through high frequency

Whether BRT is part of a transition strategy to other forms of public transport or an end in itself should be determined by how the market responds. It is not uncommon to see BRT promoted as a transition to light rail, metro and even heavy rail (e.g. in Brisbane and Pittsburgh). This is partly to get something started within constrained budgets, but to also appease anti-bus groups who see public transport as singularly rail. What is encouraging is that the success of many of the BRT systems has resulted in its expansion without the need to go to a rail solution. Carrying capacities of BRT are increasing all the time, moving the case solely for rail off many agendas *(Figure 1)*.

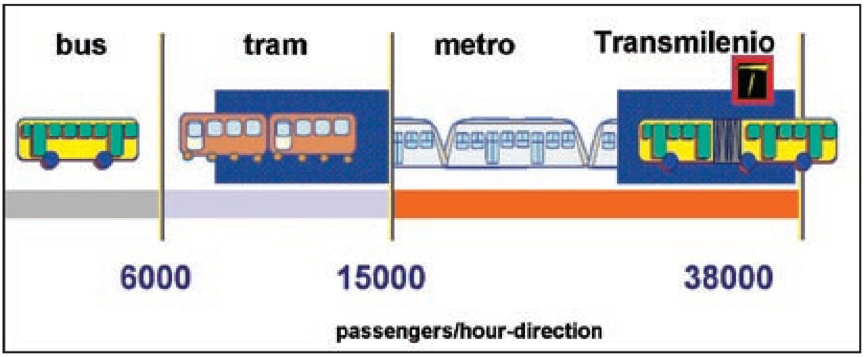
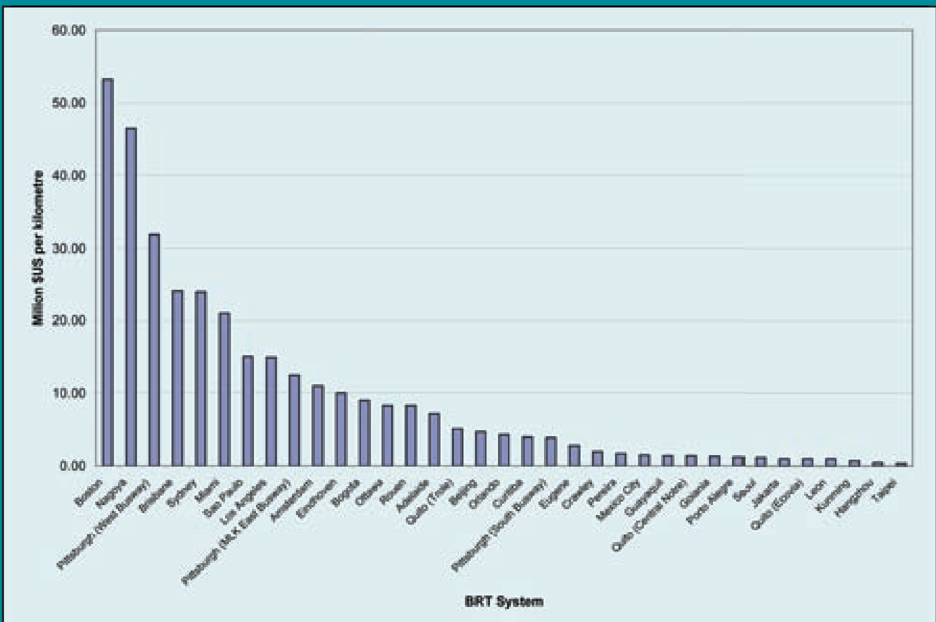


Figure 1: Changing capacity of the modes

Infrastructure Costs of BRT Systems

Infrastructure cost is one of the key indicators considered by governments and the media when debating public transport investment options. The figure below shows that the infrastructure costs for BRT systems can vary from a high of US$53.2m per kilometre in Boston to a low of US$0.35m per kilometre in Taipei. The significant range indicates the local nature of costing. In addition, the range depends upon the individual features sought within each system, e.g. quality of stations, separation from traffic. While such univariate comparisons are somewhat limiting and must be interpreted in the context of input cost differences across nations, what is surprising is that the variation does not systematically vary by country or continent, contrary to initial expectation that input costs might be greater in developed economies. For example, the 7th most expensive BRT is in Sao Paulo with the 12th in Bogota, both in Latin America. Although the least costly systems are typically in Asia and Latin America, Taipei is a relatively prosperous city with GDP per capita of US$29,500, which compares favourably with Sydney (US$33,000) and Tokyo (US$35,000). Bogota, in comparison, has a GDP per capita of US$9,000.



Total infrastructure costs per kilometre for BRT systems (2006 US$m)

The so-called natural evolution from a bus in mixed traffic to heavy rail in terms of passenger capacity per hour (sitting and standing) is no longer strictly valid. BRT systems such as the TransMilenio have shown that a BRT system can, if appropriately configured, carry more passengers per hour than many rail systems. The main trunk corridor in Bogota has maximum peak ridership of 35,000 passengers per hour per direction with recent claims of up to 45,000 passengers with maximum peak headways of 3 minutes (5 minute off-peak headways), average station dwell time of 25 seconds, with articulated buses having a carrying capacity of 160 passengers and off-vehicle smartcard fare payment. Curitiba, the forerunner to Bogota, has a maximum peak ridership of 20,000 passengers per hour per direction. This compares to the busiest rail line in Sydney, for example, of 14,000 passengers per hour per direction. In general Hidalgo (2005) states "There is a range, between 20,000 and 40,000 passengers per hour per direction, in which Metros and HBRT[1] are able to provide similar capacity. Nevertheless, there are large differences in initial costs: US$5-20 million per kilometre for HBRT, US$30-160 million per kilometre for Metros".

Figure 2 shows the peak ridership for 26 systems for which data is available. The 4 South American systems in Bogota, Sao Paulo, Porto Alegre and Curitiba have peak ridership of 20,000 or more passengers per hour per direction. This declines to 12,000 for Seoul, with the majority of systems in the range of 2,000 to 8,000 passengers per hour per direction.

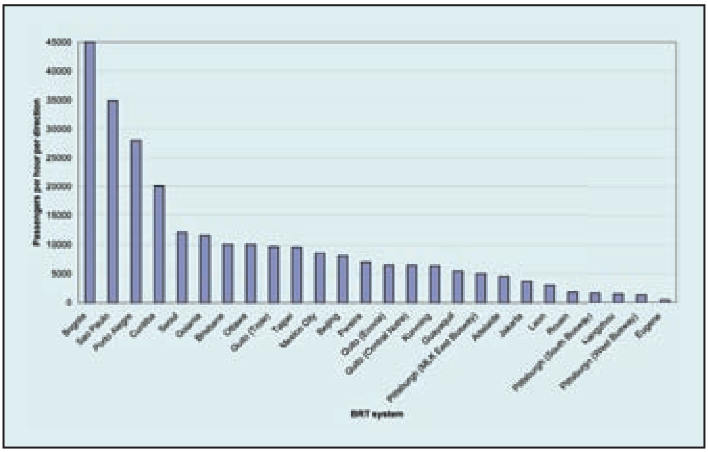


Figure 2: Peak ridership of BRT systems (2006)

The Preferred BRT Scenario

There is a significant amount of variation in the specifications of the different BRT systems. Clearly a preferred scenario would support high commercial speeds, no operating subsidies (unless they are optimal in an economic welfare sense), low floor buses with at-level boarding, dedicated corridors with no interference from other modes, smartcard off-vehicle fare payment, seamless modal interchange, and minimum access and egress time.

There is no one system that comes close to fulfilling all these conditions. The Australian and US systems deliver the highest commercial speeds, the Latin American systems are least dependent on operating subsidies, the Latin American and European systems dominate the provision of at-level boarding and alighting, the Latin American systems have been most effective in eliminating the need for signal priority or grade separation at intersections, and the Latin American, Asian, and French systems have committed to pre-board fare collection and fare verification. Modal integration at stations is strongest in Australia, Europe, and USA. Finally, the majority of BRT systems have stations spaced 500 metres apart on average, although this increases to over 1.5 kilometres for Australian and US systems, including one in China and in Holland.

Wright and Hook (2007) have compiled details of many BRT systems to document the inherent advantages and disadvantages in terms of cost and performance. With a focus on delivering a cost efficient and service effective transport system, there are opportunities today to evaluate mixtures of bus and rail systems that can service the full spectrum of capacity requirements and patronage demands (Cornwell and Cracknell 1990; Hidalgo 2005; Transit Cooperative Research Program 2007).

Conclusion

This paper reinforces the need to have a broad view on candidate public transport systems, designed to deliver network-based frequency and connectivity, while complying with value for money objectives. It is essential to stop thinking in terms of modes alone, but to think in terms of outcomes, and only then consider the role of specific modes which are a means to an end and not an end per se. The emotional debate on bus vs. rail has become somewhat counter-productive. It is time to focus on the real objective of providing sustainable transport systems that are the most affordable for the job at hand.

Notes

1. Hidalgo (2005) refers to high level BRT as HBRT, operating on its own right-of-way with high quality interchanges, integrated smartcard fare payment and efficient throughput of passengers alighting and boarding at bus stations.

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Topical issues paper

Sustainable public transport systems: Moving towards a value for money and network-based approach and away from blind commitment ☆

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Abstract

Growing public transport patronage in the presence of a strong demand for car ownership and use remains a high agenda challenge for many developed and developing economies. While some countries are losing public transport modal share, other nations are gearing up for a loss, as the wealth profile makes the car a more affordable means of transport as well as conferring elements of status and imagery of "success". Some countries however have begun successfully to reverse the decline in market share, primarily through infrastructure-based investment in bus systems, commonly referred to as bus rapid transit (BRT). BRT gives affordable public transport greater visibility and independence from other modes of transport, enabling it to deliver levels of service that compete sufficiently well with the car to attract and retain a market segmented clientele. BRT is growing in popularity throughout the world, notably in Asia, Europe and South America, in contrast to other forms of mass transit (such as light and heavy rail). This is in large measure due to its value for money, service capacity, affordability, relative flexibility, and network coverage. This paper takes stock of its performance and success as an attractive system supporting the ideals of sustainable transport.

Keywords: Bus rapid transit (BRT); Value for money; Network coverage; System

1. Introduction

There is growing support for an attractive alternative means of transportation to the car in cities. If increased public transport capacity is the way to proceed, it is very important that the investment in such systems is made in a rational way. There is a need for sensible selection and funding of technology and consideration of appropriate ways of addressing the problems attributed to the automobile. Following on from the earlier shift from heavy rail to light rail (Mackett and Edwards, 1996a, b; Edwards and Mackett, 1996), there are now signs of a shift from light rail to bus-based systems. This trend is perhaps associated with recent evidence that investment in bus rapid transit (BRT) is less risky than rail in terms of cost overruns and patronage forecasts (Flyvbjerg et al., 2004). However, there are still many examples of the use of over-sophisticated technology being used despite tight budgets and the risk of spreading thin resources even thinner.

After many years of trying to instill some sense of relevance in the debate on public transport (e.g., Kain, 1988; Hensher and Waters, 1994; Hensher, 1999), it is easy to conclude that investment in heavy and light rail is widely assumed to be the "best" solution. Unfortunately, there are at least two major deficiencies of this popular perception[1]—namely the huge cost involved (in the billions, not millions) and the inability of such a solution to deliver more than a service to specific corridors, to the neglect of the needs of the systemwide network (Kain, 1988).

It is generally agreed that improved public transport can help to solve metropolitan congestion but there are many

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[1]The Sydney debate on the role of LRT and BRT focuses on a view that buses cause congestion and light rail in the CBD will eliminate traffic gridlock. In fact, LRT would take up more space and, according to department of planning data (personal communication), buses account for less than one per cent of traffic in the central business district.

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possible ways of investing in improved public transport. These include heavy rail, light rail, and BRT, where buses have their own dedicated roads just as trains have their own dedicated track.

Globally there is growing support for delivering service capacity through BRT as a legitimate alternative to heavy and light rail within the traffic density range that many cities experience. Wright (2005) provides evidence to show that typically $ 1 billion buys 400 km of dedicated BRT in contrast to 15 km of elevated rail or 7 km of underground rail.[2] Most importantly, not only does this deliver greater network coverage but it also falsifies the traditional view of the capacity of specific public modes (buses up to 6000 passengers per hour in one direction compared to up to 15,000 for light rail/tram and over 15,000 for heavy rail/metro—see Wright 2005). Advanced BRT systems such as TransMilenio in Bogota (Columbia) can move 38,000 passengers per hour in each direction.[3] The important point should not be the capacity of vehicles but the capacity of the service. In the Sydney context, for example, buses currently deliver 5100 people an hour inbound on George Street at Railway Square in Sydney in the morning peak. The buses have the capacity to carry about 7500 an hour at 60 people a bus. Light rail's capacity is 3600 an hour at working capacity, with people sitting and standing comfortably, and 4800 an hour at crush capacity. It thus seems that the arguments about capacity do not wash! In addition, buses can seat 75% of passengers compared with 25% on light rail and, with fewer trams carrying more people, there would be longer waiting times.

There are a growing number of BRT examples around the world, and the International Union of Public Transport Operators (UITP) in Europe has recently stated that BRT is increasingly preferred over fixed rail systems for value for money. But, despite the growing evidence, there is still a powerful body of support for very expensive fixed corridor rail systems, which will fail to serve the fuller demands of many metropolitan areas.

One problem is summarised in the adage 'trains are sexy and buses are boring' (Richmond, 1998; Hensher, 1999). The challenge is to get away from thinking of BRT as those awful polluting buses that get delayed because they compete with cars (even if they are occasionally offered disconnected bus lanes). This is not BRT! BRT has its own dedicated right of way (all be it narrower and less intrusive than that required for light rail transit (LRT) and, as to pollution, one should think of starting the investment in BRT (as cities such as Curitiba, Brisbane, Taipei, Bogota, and Pittsburgh have done) with clean-fuelled buses.[4] Electrically powered rail may have limited impact on the local air quality but it requires unsightly power lines and, particularly if sourced from coal-fired power stations, may be responsible for significant greenhouse pollution.

There is a need to set aside dedicated 'roads' for BRT to achieve its potential, not only in the inner city-CBD area but also across a metropolitan network. Crucially, the technology must not be the determining influence; rather the way forward is to identify systems (i.e., integrated vehicles and infrastructure) that will provide a high level of service capacity throughout a connected network, delivering frequency, connectivity, and visibility.[5] Public transport improvements must be part of a larger package in which we consider ways of financing these improvements, and a good start is to learn from the experiences of London and Stockholm where a congestion-charging scheme is in place. The money raised in London and Stockholm is earmarked for investment into public transport—surely a sensible strategy. Most importantly the politicians have earned respect for taking such an initiative. All of this seems so obvious in many ways; yet will other world cities rise to the occasion?

What about the future for bus systems? Despite the growing appeal of bus-based transitways, there is still a lot that can be achieved by simple solutions such as adding more buses, adjusting fare schedules, improving information systems, and integrating ticketing. Unfortunately, these incremental improvements may be ignored if the debate concentrates on the relative merits of special rights-of-way for buses as against light rail. Buses, especially bus-based transitway systems, are arguably better value for money, and if designed properly, can have the essential characteristics of permanence and visibility claimed to be important to attract the property development, which is compatible with medium to high-density corridor mobility. Newman and Kenworthy (1989) suggest that good rail transit systems provide the opportunity for highlighting public values in ways, which give a city new pride and hope for the future. While this may have some truth, it should not deny the capability of achieving the same impact with a high-quality dedicated bus-based transitway; indeed, it may be argued that the images created in promotion of the Liverpool–Parramatta transitway in Sydney and the Brisbane busway system are actually more appealing to civic pride than the existing heavy and light rail systems.

An assessment of BRT systems throughout the world suggests that their cost structures impose less burden on taxpayers in subsidies per passenger than does LRT. Thus, for any given amount of investment, the environmental, energy, and traffic reduction benefits of BRT are likely to be much higher than LRT. Because it can offer more direct origin to destination service, BRT can provide higher quality service by avoiding time-consuming transfers, and by using modern technology, the vehicles, stations, and rights of way of BRT systems can be very attractive.

[2]Even if these numbers are debatable and subject to error, the differences are sufficiently stark to be worthy of note.

[3]Personal communication with TransMilenio.

[4]Diesel technology has come a long way in reducing emissions, with the new Euro 3 buses emitting less than natural gas buses.

[5]By which we mean a physical presence, which indicates where the services run to and from.

Importantly, BRT can be built much faster than competing systems and is more adaptable to changing travel patterns.

2. The appeal of BRT

BRT has shown to be an effective catalyst to help transform cities into more liveable and human-friendly environments. The appeal of BRT is the ability to deliver a high-quality mass transit system within the budgets of most municipalities, even in low-income cities. BRT has thus proven that the barriers to effective transit are not costly or high technology. The principal ingredient is simply the political will to make it happen (Wright and Hook 2006, preface).

There is growing evidence around the world, in origin–destination density contexts similar to the locations proposed for light rail, that a dedicated BRT system (i.e. road infrastructure dedicated exclusively to buses as in Brisbane, Curitiba, Bogota, Pittsburgh, Ottawa etc.) can carry the same number of people as light rail for a typical cost 4–20 times less than a LRT system and 10–100 times less than a heavy rail system (USA General Accounting Office, 2001). It is flexible, it is as permanent as light rail and it can have the image of light rail (rather than the image of boring buses) if planned properly. The USA General Accounting Office (2001) audit of BRT and light rail in six US cities found that the capital cost per mile for LRT compared to BRT in its own lane was 260% more costly. Comparisons with BRT on street or on an HOV lane are not useful and have been excluded. When one also notes BRT's lower operating costs for both institutional[6] and maintenance reasons, the case is clear.

The 16 km state-of-the-art south east busway in Brisbane, opened in 2000, is an example of a busway system that has exceeded expectations in patronage. In the first 6 months of operation, the number of passengers grew by 40% or by more than 450,000, giving a daily average of 58,000. Over the first 3.5 years there has been an 88% increase in patronage. It has been reported (The Urban Transport Monitor, 2002) that 375,000 private vehicle trips have been converted to public transport. Pittsburgh's 8 km third busway, which opened in September 2000, secured average weekday patronage growth of 23% over the first 17 months. Current Pittsburgh average daily passenger trips on the full busway system of 43.8 km is 48,000 and growing steadily.

On a number of reasonable assumptions, the patronage potential for a bus-based transitway can be as high as twice that of LRT. Results of Port Authority's busways[7] suggest that the average operating and maintenance costs per rider (FY 1995 data) are south busway = \$1.03; east busway = \$0.95; remainder of bus system = \$2.55; light rail system = \$3.22. Operating costs for Pittsburgh's east and south busways (1989) averaged \$0.52/passenger trip while cost/passenger trip for light rail lines in Buffalo, Pittsburgh, Sacramento, and San Diego averaged \$1.31[8] Sislak (2000) undertook a comparison between light rail and BRT options in Cleveland and Nashville: Cleveland's operating and maintenance costs are around one sixteenth that for the light rail option and capital costs are just over a quarter of that estimated for the light rail option; Nashville's capital cost for BRT under half of that estimated for light rail option (at grade). Operating and maintenance costs for LRT estimated to be \$4.6 million annually (\$18.28 per LRT car mile). BRT operating and maintenance costs estimated to be \$3.2 million annually (\$12.73 per bus mile). The relativities will be determined by the sophistication of the design of the bus-based transitway system. Establishing actual patronage is another issue, although we have yet to find any unambiguous evidence to suggest that you can attract more people to LRT than a bus-based scheme. This arises because of the difficulty of finding very similar circumstances in which both LRT and a geographically comparable bus-based system are in place. Certainly the performance of the dedicated bus-based transitway systems in Curitiba, Bogota (Estache and Gomez-Lobo, 2005), Brisbane, Pittsburgh, and Ottawa deserve closer scrutiny.

Menckhoff (2005) has reviewed the specifications and performance of 10 existing BRT systems (totalling 320 km) and 11 systems (adding another 240 km) that will be in place within two years in Latin America as part of a World Bank assessment. Describing Latin America as a 'fascinating urban transport laboratory', Menckhoff documents the distinctive image and high productivity of public transport systems that has arisen out of the South American initiatives. Key to the success is institutional reform and the specification of a BRT system that delivers feeder-trunk operations, bus overtaking at stops, four lane (2+2) busways for high-demand corridors, limited stop and express services, high-capacity trunk-line articulated (18 m, 160 passenger) and bi-articulated (25 m, 260 passenger) vehicles, high-level 'heavy rail-like' entry into buses often through centrally located bus stations, and prepayment of fares. A novel reverse of practice elsewhere is the decision to elevate the bus stop/station platform so that buses can be built on a truck chassis, which is much less costly than low-floor buses. In addition, two-directional bus stations in the median were first introduced in Bogota's TransMilenio, which required offside doors for all trunk-line buses. This has the advantage of savings in physical space and station labour.

BRT in Latin America has shown itself to be capable of moving passengers at a fraction of the cost of other high-capacity modes; and most importantly has helped to reshape the less than desirable image of road-based public transport. The political windfall has been substantial to the

[6]In some countries, BRT avoids the stranglehold that rail unions often have on the system, usually leading to inflated costs.

[7]see http://131.247.19.10/media/presents/trb-04/wohlwill.pdf.

[8]See http://trb.org/publications/tcrp/tcrp_rpt_90v2.pdf.

Mayors responsible for their implementation. A limited comparison of selected BRT, light rail, elevated rail, and subway systems suggests the appeal of BRT in terms of passenger flows and costs. At relatively high commercial speeds (15–32 km/h), Curitiba is carrying peak volumes in excess of 14,000 passengers/h/direction, increasing to over 20,000 passengers/h/direction where extra passing lanes are provided at bus stops. In Bogota the Transmilenio double-width busway accommodates 35,000 passengers/h/direction with a mixture of all-stop and express bus services (Menckhoff, 2005).

The success of BRT in Latin America should not be seen as a regional peculiarity but rather a reflection of the particular period in time in which opportunities to work with specific technologies has occurred. Light rail is more common in Europe, in large part due to the inertia associated with the availability and promotion of this technology by European manufacturers in earlier periods. Bouf and Hensher (2006) indicate that part of French strategy to support public transport was the desire to create an industry with public subsidies in conformity with the "colbertist" model and to export public transport technology, especially LRT.[9] To a certain extent this has been successful although the main expected market (China) is now heading increasingly toward BRT rather than LRT. The demonstrable success of BRT in South America is clearly changing the terms of the debate!

A recent by the Canadian Urban Transit Association (2004) identified a number of major benefits of BRT, which have repeatedly been reported in many other jurisdictions:

- *Service speed and reliability*: With average operating speeds of 45–50 km/h and consistent travel times, BRT services on busways and bus lanes are more attractive than conventional transit routes operating at half that speed and with lesser reliability due to congestion.
- *Greater patronage*: BRT projects build patronage because they offer a premium service with faster speeds and greater reliability. The use of special branding to promote BRT services also helps attract new users.
- *Lower costs*: The faster average speeds of BRT reduce operating costs and BRT facilities cost less to build than light rail because they do not need specialized electrical, track, vehicle maintenance or storage infrastructure.
- *High capacity*: High-capacity vehicles, frequent service, and flexible routing structures allow BRT to match or exceed the passenger volumes of the busiest light rail systems.
- *Operational flexibility*: BRT allows a variety of customer services, with a single running way able to support express, local and skip-stop services—a difficult and expensive proposition in a rail environment.
- *Incremental implementation*: BRT systems can be implemented in stages. Buses can use a BRT facility to travel through a congested area, then switch onto a roadway to serve a relatively uncongested corridor.
- *Land use change*: BRT can stimulate the development or redevelopment of compact, pedestrian- and transit-friendly land uses, when supported by complementary land use and zoning policies. This contradicts the claims by proponents of light rail that only rail-based investments can deliver such development stimulus because it is 'permanent'.

A review of US BRT experience (Federal Transit Administration, 2004) indicated significant increases in transit patronage in virtually all corridors where BRT has been implemented. Though much of the patronage increases have come from passengers formerly using parallel service in other corridors, passenger surveys have revealed that many trips are new to transit, either by individuals who used to drive or be driven, or individuals who used to walk, or by individuals who take advantage of BRT's improved level of service to make trips that were not made previously. Aggregate analyses of patronage survey results suggest that the patronage increases due to BRT implementation exceed those that would be expected as the result of simple level of service improvements. This implies that the identity and passenger information advantages of BRT are attractive to potential BRT customers. Patronage gains of between 5% and 25% are common. Significantly greater gains, such as 85% in Boston's Silver Line represent the potential for BRT.

3. Conclusions

This short paper is designed to reinforce the appeal of BRT systems over other public transport investment strategies. The growing evidence globally about the broad-based advantages of BRT over other systems such as light rail, and even heavy rail in some density contexts, is so strong on the main measures of performance that, at the very least, all governments should seriously evaluate the appeal of BRT. We acknowledge the big challenge in even referring to buses, given the emotional overtones and imagery that has not served the bus well in the past. But the incessant contrasts between buses in mixed traffic and light rail (which often mixes with other traffic), has failed to capture the real meaning of a BRT system in which the buses move along dedicated infrastructure. The challenge is to continue, through evidence, to reinforce this position and hopefully to move away from un- and mis-informed blind commitment to sensible outcome-based decision making.

Acknowledgement

The comments and editorial magic of Peter Bonsall have materially improved this paper.

[9] We understand that part of the reason for the popularity of LRT over BRT in France is attributable to the availability of significant discounts on capital costs—even though this does not solve the problem of ongoing high maintenance and operating costs.

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Bus rapid transit systems: a comparative assessment

David A. Hensher · Thomas F. Golob

Abstract There is renewed interest in many developing and developed countries in finding ways of providing efficient and effective public transport that does not come with a high price tag. An increasing number of nations are asking the question—what type of public transport system can deliver value for money? Although light rail has often been promoted as a popular 'solution', there has been progressively emerging an attractive alternative in the form of bus rapid transit (BRT). BRT is a system operating on its own right-of-way either as a full BRT with high quality interchanges, integrated smart card fare payment and efficient throughput of passengers alighting and boarding at bus stations; or as a system with some amount of dedicated right-of-way (light BRT) and lesser integration of service and fares. The notion that buses essentially operate in a constrained service environment under a mixed traffic regime and that trains have privileged dedicated right-of-way, is no longer the only sustainable and valid proposition. This paper evaluates the status of 44 BRT systems in operation throughout the world as a way of identifying the capability of moving substantial numbers of passengers, using infrastructure whose costs overall and per kilometre are extremely attractive. When ongoing lifecycle costs (operations and maintenance) are taken into account, the costs of providing high capacity integrated BRT systems are an attractive option in many contexts.

Keywords Bus rapid transit · Comparative analysis · Infrastructure costs · Service levels

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Introduction

Public transport investment is being touted as a key springboard for a sustainable future, especially in large metropolitan areas with growing populations. Whether such investment will turn the tide away from automobility is a big question; however regardless of the likely outcome, any commitment to improved public transport has a growing number of options to pursue. Although variations in rail systems typically loom dominant in many strategic statements on urban reform (Sislak 2000; Edwards and Mackett 1996), ranging from heavy rail through to metro rail and light rail, there is a growing interest worldwide in ways of making better use of the bus as a primary means of public transport, and not limited as a service that feeds a rail network (Hensher 1999, 2007; Canadian Urban Transit Association 2004; Federal Transit Administration 2004).[1]

There are many ways in which bus transport can be developed as part of an integrated network-based public transport system, typified by the best practice bus rapid transit (BRT) systems in South America such as Curitiba in Brazil and TransMilenio in Bogota, Colombia (Menckhoff 2005). Bus Rapid Transit is "…a high-quality bus based transit system that delivers fast, comfortable, and cost-effective urban mobility through the provision of segregated right-of-way infrastructure, rapid and frequent operations, and excellence in marketing and customer service. BRT essentially emulates the performance and amenity characteristics of a modern rail-based transit system but at a fraction of the cost. A BRT system will typically cost four to 20 times less than a light rail transit (LRT) system and 10 to100 times less than a metro system." (Wright and Hook 2007, 11).

Wright and Hook (2007) have compiled details of many BRT systems to document the inherent advantages (and disadvantages) of many of the systems in terms of cost and performance. With a focus on delivering a cost efficient and service effective transport system, there are opportunities today to evaluate mixtures of bus and rail systems that can service the full spectrum of capacity requirements and patronage demands (Cornwell and Cracknell1990; Hidalgo 2005; Transit Cooperative Research Program 2007).

What is especially pertinent however is the recognition that the so-called natural evolution from a bus in mixed traffic through to heavy rail in terms of passenger capacity per hour (seating and standing) is no longer strictly valid. BRT systems such as the TransMilenio have shown that a BRT system can, if appropriately configured, carry more passengers per hour than many rail systems. The main trunk corridor in Bogota has peak maximum ridership[2] of 35,000 trips per hour[3] one way with 3 min maximum peak headways (5 min off-peak headways) with buses spaced much closer together much of the peak, average station dwell time of 25 s, with articulated buses having a carrying capacity of 160 passengers and off-vehicle smartcard fare payment. Curitiba, the forerunner to Bogota, has a peak maximum ridership of 20,000 trips per hour one way. This compares to the busiest rail line in Sydney, for example, of 14,000 trips per hour one way. In general Hidalgo (2005, 5) states "There is range, between 20,000 and 40,000 passengers/hour per direction, in which Metros and HBRT[4] are able to provide similar capacity. Nevertheless,

[1] Discussions with Raymond Lam, Singapore's Minister of Transport, have been useful in highlighting this position.

[2] For 35,000 passengers with a load of 160, there would need to be 219 buses in the peak hour, or almost four buses each minute.

[3] With recent claims of up to 45,000 trips per hour.

[4] Hidalgo (2005) refers to high level BRT as HBRT.

there are large differences in initial costs: US$5-20 million per kilometre for HBRT, US$30-160 million per kilometre for Metros".

As interest in BRT systems grow, questions are being asked about the actual cost and carrying capacity of such systems. To investigate these and other matters, we have taken the tables prepared by Wright and Hook (2007 appendices) together with some enhancements, and developed a data base to assess the relationship between infrastructure cost ($US total and per kilometre), carrying capacity (passengers per hour per direction), and the specifications of each system in terms of service frequency, fares and fare payment system, trunk and feeder capacity and connectivity, extent of separation from other modes, speed, station spacing, dwelling times etc. In any comparison between countries, however, we recognise the difficulties where inputs have substantially different prices, time periods, and baseline conditions prior to construction[5]; nevertheless, there are very important insights that can be gained to provide broad guiding signals on the appeal of very specific investment strategies to grow public transport patronage and deliver value for money in terms of the cost of providing a given level of service relative to other forms of public transport.

This paper is structured as follows. The next section provides a descriptive overview of the key dimensions of the 44 BRT systems, enabling an appreciation of capability. Such a commentary, while informative, is limited in that the role of each feature of the BRT system needs to be assessed in terms of its influence on cost and patronage, given the level of service. This is presented in Sects. 3 and 4 using a multivariate analysis to reveal candidate influences on variations in infrastructure costs and daily ridership. The paper concludes with suggestions for an ongoing monitoring program to keep the accumulating evidence current.

Descriptive contrasts of BRT systems

Data on 44 BRT systems around the world, compiled by Wright and Hook (2007), provides the only 'comprehensive' source of information that has reasonably comparable data. This data, focussed on the BRT component on integrated systems, including any connection to a feeder network, is not without a large amount of missing items across the 44 systems and indeed not all commentators agree with the actual information provided[6]; however, there is enough useful information to begin to appreciate the nature of each system and, in particular, to identify the key features that are systematically varying sources of influence on infrastructure costs. We have 70 data items per BRT system (see Appendix), some of which are more complete in details than others. We have selected the data indicators that are relatively complete and which are plausible candidates for testable hypotheses on what may be key sources of systematic variation in infrastructure costs overall and per kilometre.

[5] One reason for differences in infrastructure costs relates to the physical conditions prior to start of construction, which are difficult to define. Adelaide, for example, started from scratch, although they had the advantage that most of the land was in Government ownership, but they had to build a lot of bridges. Bogota, in most cases, converted some existing road lanes into BRT lanes.

[6] Like any highly aggregate analysis that summarises the dimensionality of each system by a single average indicator, the data will be subject to disagreement, and indeed would display varying deviations around specific averages depending on the source used to obtain the data. Despite this, there is some useful broad evidence that signals specific strengths of BRT systems in respect to costs and ridership.

It is not unreasonable to assume that the two primary transport indicators that attract the attention of governments and the media in particular are infrastructure costs (Fig. 1) and patronage levels (Fig. 2). The infrastructure costs in $US2006m per kilometre in Fig. 1 vary from a high of $53.2m per kilometre in Boston to a low of $0.35m per kilometre in Taipei. The significant size of the various ranges indicates the local nature of costing. Additionally, the range depends upon the individual features sought within each system (e.g., quality of stations, separation from traffic). We recognise that such univariate comparisons are somewhat limiting and must be interpreted in the context of input cost differences across nations. However, what is surprising is that the variation does not systematically vary by country or continent, given an initial expectation that input costs might be greater in developed economies. For example, the seventh most expensive BRT is in Sao Paulo with the 12th in Bogota, both in Latin America. Although the least cost set are typically in Asia and Latin America, Taipei is a relatively prosperous city with GDP per capita of $US29,500, which compares favourably with Sydney ($US33,000) and Tokyo ($US35,000). Bogota is $US9,000 per capita.

Peak ridership for 26 systems for which we have data shows four South American systems (Transmilenio in Bogota, Sao Paulo, Porto Alegre, and Curitiba) with 20,000 passengers per hour per direction, which then declines to 12,000 (Seoul), with the majority of systems in the 2,000 to 8,000 passengers per hour per direction.

Candidate influences on variations in infrastructure costs per kilometre, based on the extant literature, and the knowledge of public transport systems in general that are provided in the data set, are summarised in a series of Figs. 3–9. They are: commercial speed, need for operating subsidies, at-level boarding and alighting, signal priority or grade separation at intersections, pre-board fare collection and fare verification, modal integration at stations, and average distance between stations.

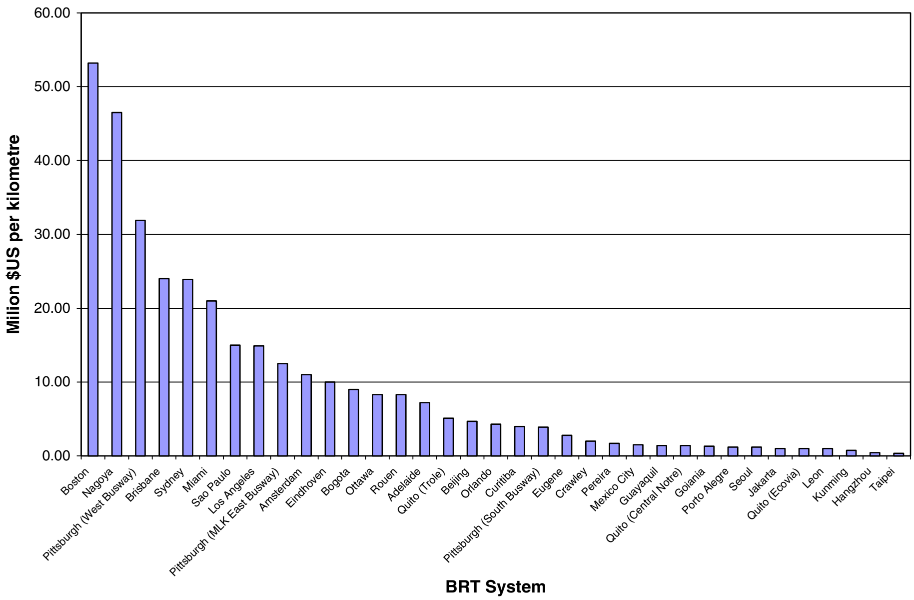

Fig. 1 Total infrastructure costs per kilometre ($m2006)

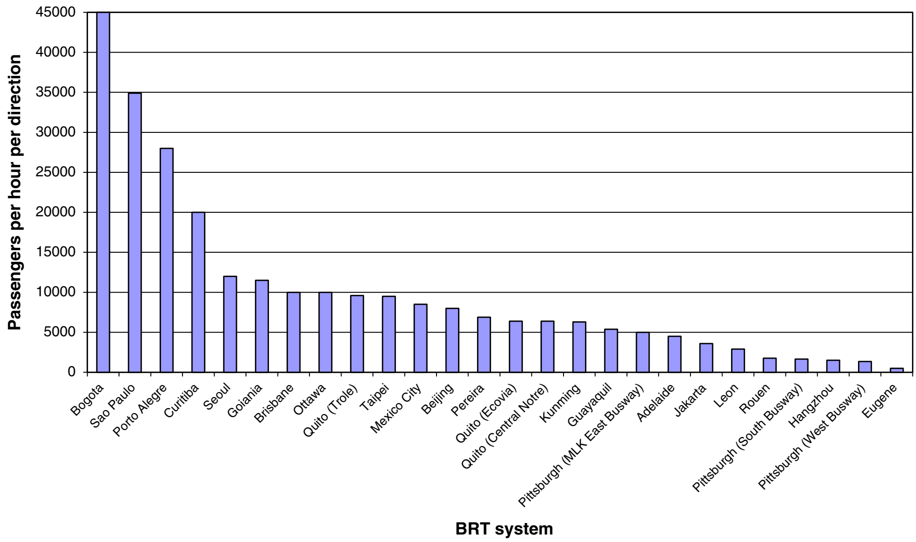

Fig. 2 Peak ridership (2006)

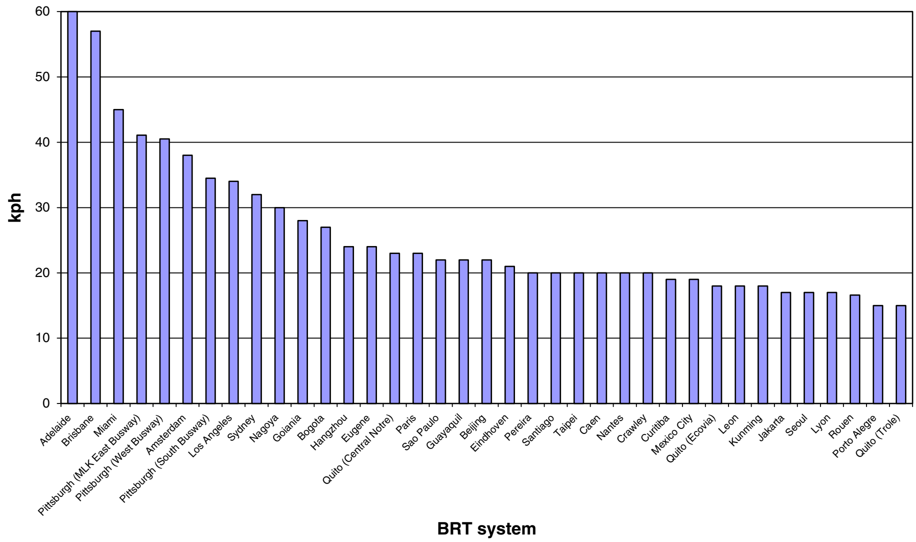

Fig. 3 Average all day commercial speed (various years in 2000–2006)

A careful assessment of these figures shows a significant amount of variation in the specifications of each system. Clearly a preferred scenario would support high commercial speeds, no operating subsidies (unless they are optimal in an economic welfare sense), low flow buses with at level boarding, totally dedicated corridors with no interference from other modes (which is an attractive feature of railways), smart card off-vehicle fare payment, seamless model interchange (where it occurs), and minimum access and egress time. There is no one system that comes closest to fulfilling all these conditions. The Australian

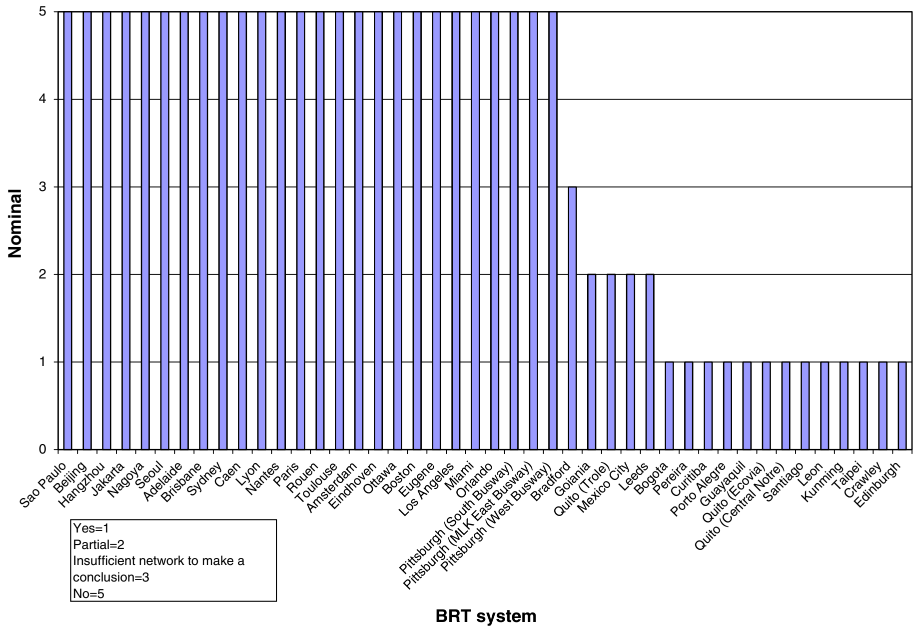

Fig. 4 No need for operational subsidies (2006)

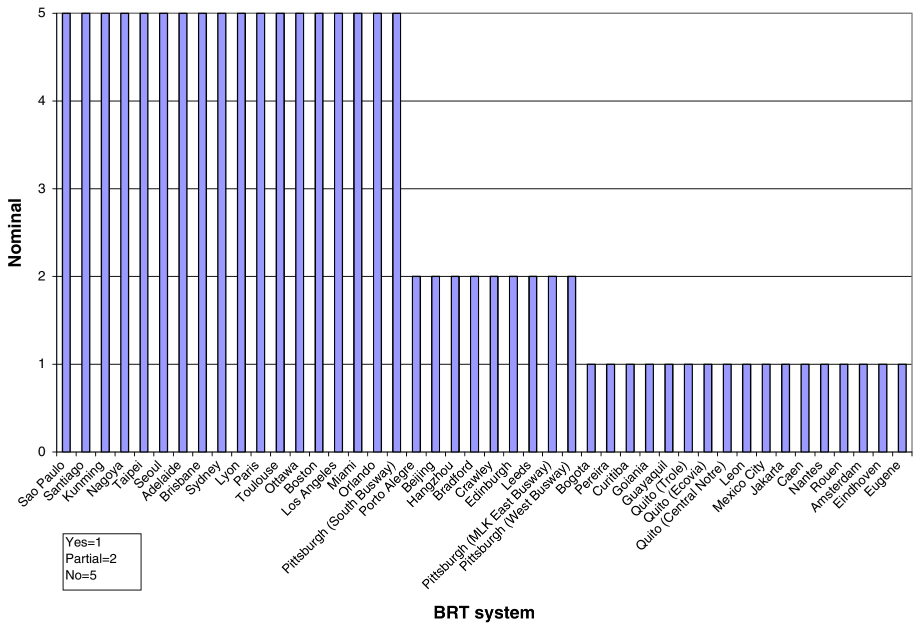

Fig. 5 At-level boarding and alighting (2006)

and US systems deliver the highest commercial speeds, the Latin American systems are least dependent on operational subsidies, the Latin American and European systems dominate the provision of at-level boarding and alighting, the Latin American systems

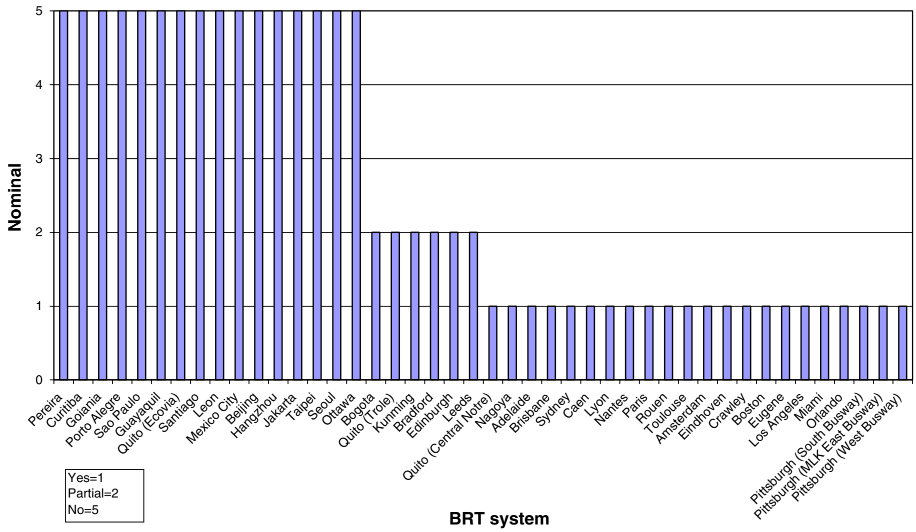

Fig. 6 Signal priority or grade separation at intersections (2006)

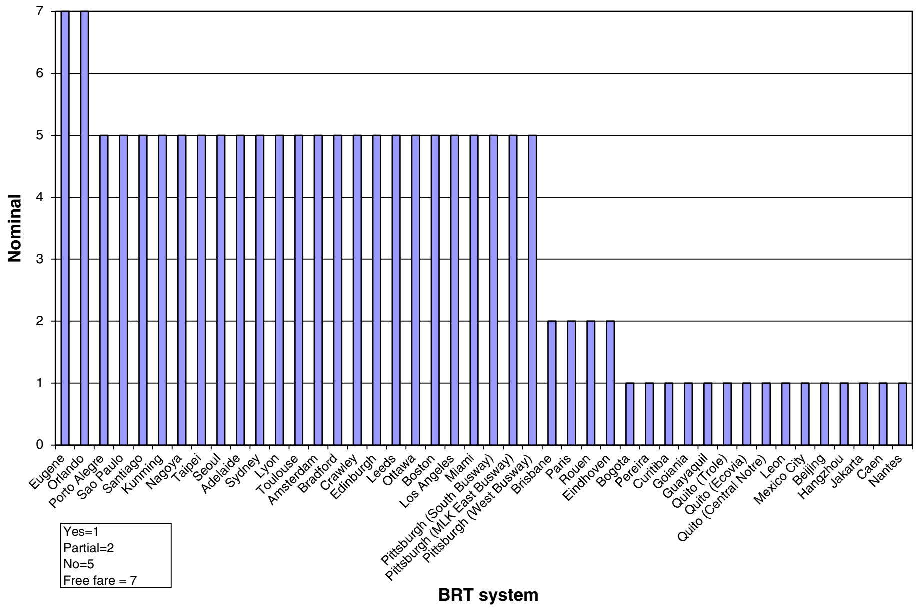

Fig. 7 Pre-board fare collection and fare verification (2006)

have been most effective in eliminating the need for signal priority or grade separation at intersections, and the Latin American, Asian, and French BRT systems have committed to pre-board fare collection and fare verification. Modal integration at stations is strongest in Australia, Europe, and USA. Finally, the majority of BRT systems have stations spaced apart on average 500 m, although this increases to over 1.5 km for Australian and USA systems including one in China and in Holland.

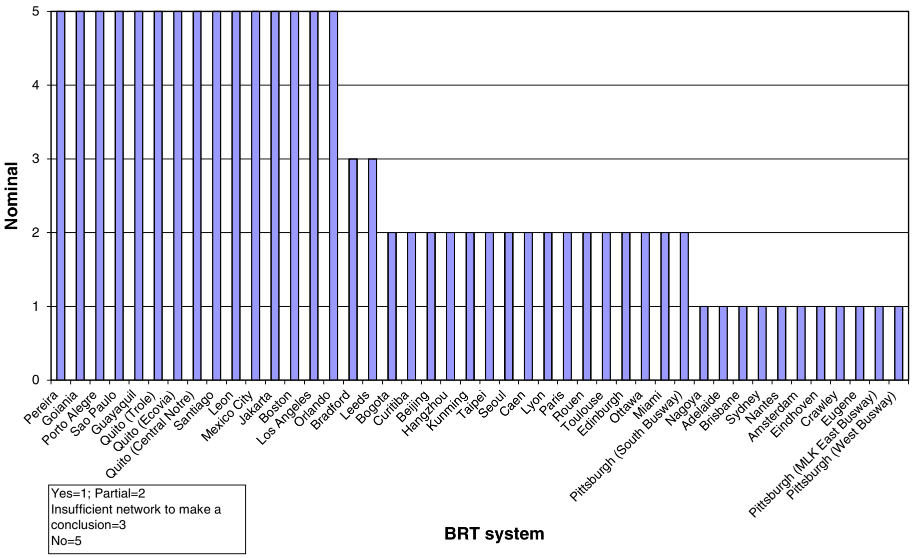

Fig. 8 Modal integration at stations (2006)

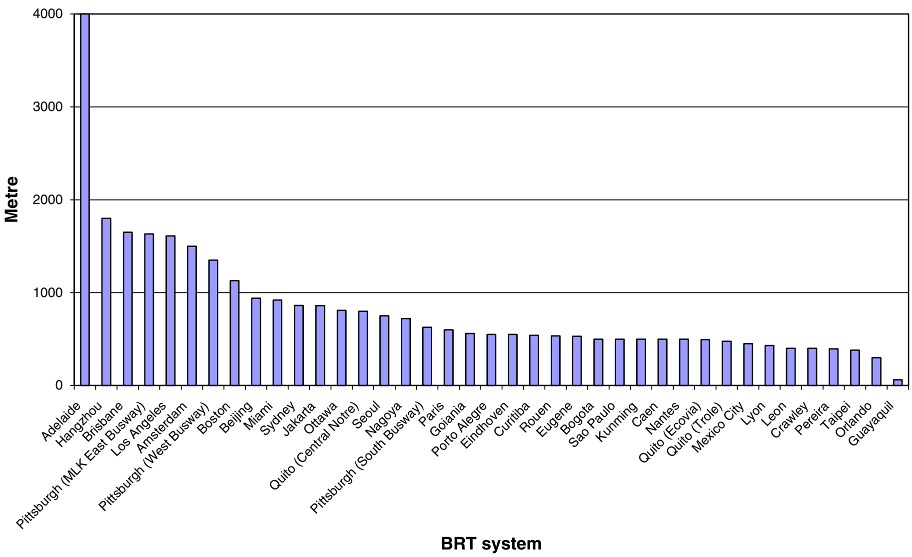

Fig. 9 Average distance between stations (2006)

This brief commentary highlights a very important feature of this comparison. Given the interest in establishing the infrastructure cost and patronage profile of all BRT systems for which data is captured, and recognizing the large variation in design and service levels with no obvious mapping between features and specific systems, it is necessary to develop a more formal multivariate framework within which to identify the influence that specific design elements have in explaining differences in infrastructure costs in total and per kilometre, and patronage per day across the BRT systems.

Assessment of systematic sources of variation in infrastructure costs

A two-stage empirical process was used to establish sources of systematic variation in (i) infrastructure costs per kilometre and (ii) total infrastructure costs. It was, however, preceded by a review of the literature (Canadian Urban Transit Association 2004; Federal Transit Administration 2004; Menckhoff 2005; Cornwell and Cracknell 1990; and Hildago 2005)[7] as the basis of establishing a series of research hypotheses. The main factors likely to have an influence on infrastructure costs are suggested to be input costs in construction, the year(s) of construction, the funding source, the number and size of stations and terminals, and the extent to which a full BRT treatment is implemented, or degrees of light treatment in terms of components such as intersections and signalization.

Within the limitations of the data, we began with an assessment of the nominal scaled variables listed in Appendix Table A1, using a technique known as nonlinear canonical correlation analysis (NLCCA) that searches for the optimal scale (or cut-off points) for each variable, including those variables that 'represent' the identified sources from the literature review. We report the evidence only for infrastructure costs per kilometre in the Appendix. What we found (see Appendix Table A2), with rare exception, was a high amount of association between infrastructure costs and explanatory variables that we would argue have little to do with infrastructure costs (e.g., 'operating subsidy requirements' and the 'management of the fare system'); and only two statistically significant dummy variables that made causal sense, i.e., at-level boarding and signal priority at intersections; the latter being identified in the literature review. Given that the dependent variable is expressed as a cost per kilometre we also defined candidate explanatory variables in per kilometre units (e.g. number of intersections with priority signal control and grade-separated per trunk kilometre, and the 'number of terminals per trunk kilometre); however this did not alter the essential statistical message reported in the Appendix.

We undertook the same analysis using a dummy coded multivariate analysis (Table A3) with 11 variables that explain 74.2% of the variation in infrastructures cost per kilometre. We then investigated the ratio scale variables (listed in Appendix Table A1) while initially retaining the two significant casual effects above as dummy variables, handled through traditional ordinary least square regression.

The main findings are given in Table 1 for both total and unit infrastructure costs, after taking in account the exploratory analysis in the Appendix. Model specifications where the dependent variable is unit infrastructure cost, and in which the 'number of intersections with priority signal control and grade-separated' and the 'number of terminals' defined on a per trunk kilometre (and included in these units and as a natural logarithm), all resulted in statistically insignificant parameters (ranging from 0.30 to 1.74); and so the absolute levels were selected. This is defensible in that these variables are sensible indicators of the

[7] A referee suggested we undertake a comparison with other public transport systems (i.e., heavy and light rail). We have resisted this since the focus herein is on BRT per se, and understanding what factors may contribute to variations in unit and total infrastructure costs. The debate on the comparative cost of BRT, light rail and heavy rail is reported in other papers in the literature (see for example, Edwards and Mackett 1996; Hensher 1999, 2007a, Chap. 17; Vuchic 2007).

Table 1 Infrastructure cost regression models

Explanatory variable	Estimated parameter	
	Model 1	Model 2
Natural Log of age of BRT system	0.1839 (1.74)	0.2896 (2.09)
Number of intersections with priority signal control and grade-separated	0.0410 (3.62)	0.0396 (3.76)
Number of terminals	0.0517 (2.38)	0.1457 (6.99)
Boston BRT (1,0)	3.4281 (16.51)	3.0988 (15.6)
Pittsburgh West BRT (1,0)	2.7198 (12.83)	1.9695 (9.00)
Constant	0.2868 (0.96)	2.83621 (10.7)
Adjusted R^2	0.559	0.590
Sample size	28	28

Dependent variable: Model 1 = natural logarithm of infrastructure cost ($USm per kilometre); Model 2 = natural logarithm of infrastructure cost ($USm). *t*-ratio in brackets

additional investment cost involved in delivering, on average, each system kilometre, and which proxy for important dimensions of a BRT network, similar to way that network variables are entered in absolute terms in the decomposition of key performance indicators (such a total cost per kilometer—see Hensher (2007a, Chap. 13).

In recognition of the significant variation in infrastructure costs, we introduced a series of BRT specific dummy variables to control for the possibility of bias at the upper end (see Fig. 1). We found initially that capturing this for the three most expensive systems (Boston, Nagoya, and Pittsburgh West) was sufficient, with non-statistically significant BRT system-specific dummy variables after the top three. However the final model eliminated the Nagoya system due to missing data, and hence only two dummy variables remained. Overall, 55.9% of the variation in unit infrastructure costs, and 59% of the variation on total infrastructure costs, across 28 systems can be explained by five variables. This is a satisfying result for disaggregated data on very different systems in terms of scale and configuration. In one sense the models in Table 1 are a reduced form in which variables such as the age of the BRT is capturing other effects as suggested below. We were unable to find any statistically significant influence of location based on developed vs. developing economies, and between developed economies (e.g., West Europe, USA/Canada, Asian economies (including Japan, Tawain and Korea)).

We introduced the natural logarithm of the number of years up to 2007 that the BRT system has been in place, to control for any differences in cost due to age, as suggested by the literature review. The average age is 7.8 years with a range from 1 to 35 years (Fig. 10). Given that the dependent variable and the age variable are logarithmic, the parameter estimate is a mean elasticity effect, which indicates that, all other influences being held constant, that a ten percent increase in age results in a 1.839% increase in cost per kilometre or a 2.896% increase in total infrastructure cost (in $US2006). What this suggests is that through time, on average, total and unit infrastructure costs, after adjusting for inflation, have declined, possibly because of the nature of the BRT system baseline (e.g., less major engineering such as bridges and upgrading of existing roads and construction on the surface) and a fall in the real price of inputs. Although the variations linked to age may not be of such great relevance, given that this will vary by context, it is important that we control for this potential bias in assessing the influence of other systematic sources of cost variation.

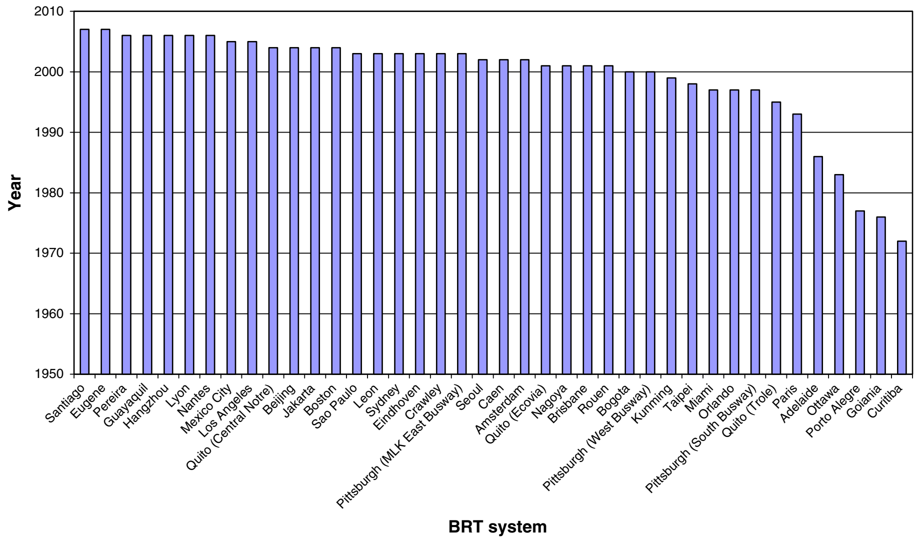

Fig. 10 Age profile of BRT systems (2006)

We can clearly see that there are two very influential design delivery features that are systematically linked to the costs of infrastructure and which were suggested by the literature review; namely the number of terminals and number of intersections with priority signal control and grade-separated.

Assessment of systematic sources of variation in ridership

We also investigated the potential sources of influence on patronage, defined as the number of total system passenger-trips per day per kilometre.[8] The candidate influences in the data set are: fares, the number of stations, the average distance between stations, average all day commercial speed, average peak headway, average non-peak headway, and vehicle capacity. Subsets of these continuous variables are highly correlated, and so after accounting for this, we identified four statistically significant influences on patronage—the number of stations, the average peak headway (in minutes) (see Figs. 11 and 12), vehicle capacity, and fares.

A number of system variables were found to have a statistically significant influence on passenger trips per day, as summarised in Table 2. It should be noted that the model estimated is not a demand model in the fuller sense of accounting for competing modes and the influence of the socio-economic context; rather it is a representation of a model designed to identify the potential influence of BRT design, service and fares on passenger trips per day, holding all other possible influences constant at an average level that is capture by the constant. The findings are encouraging, representing, all other influences held constant, two of the most important influences on growing public transport—connectivity and patronage, together with vehicle capacity and fares. All other things being

[8] We adjusted the ridership figures by dividing by kilometres of corridors to correct for any comparisons that would tend to deliver higher patronage simply because of the amount of coverage regardless of the role of other factors.

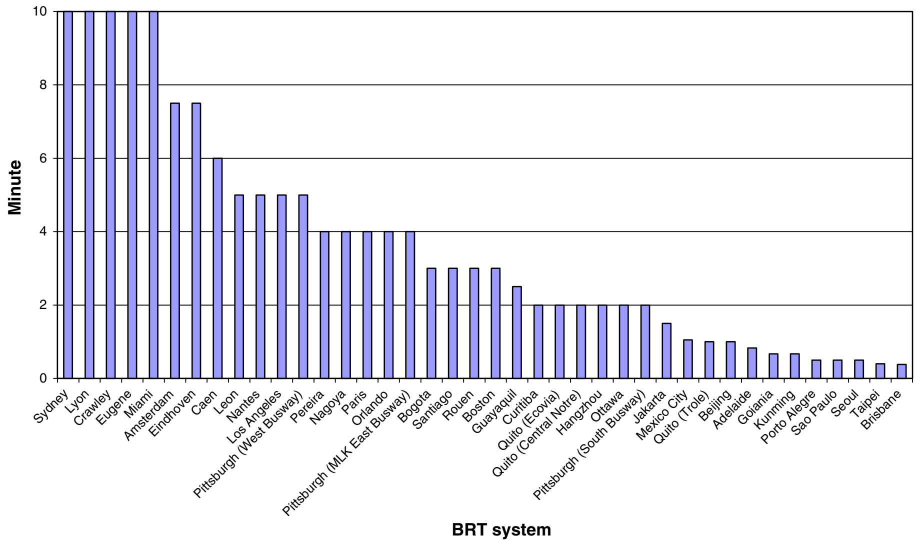

Fig. 11 Average peak headway (2006)

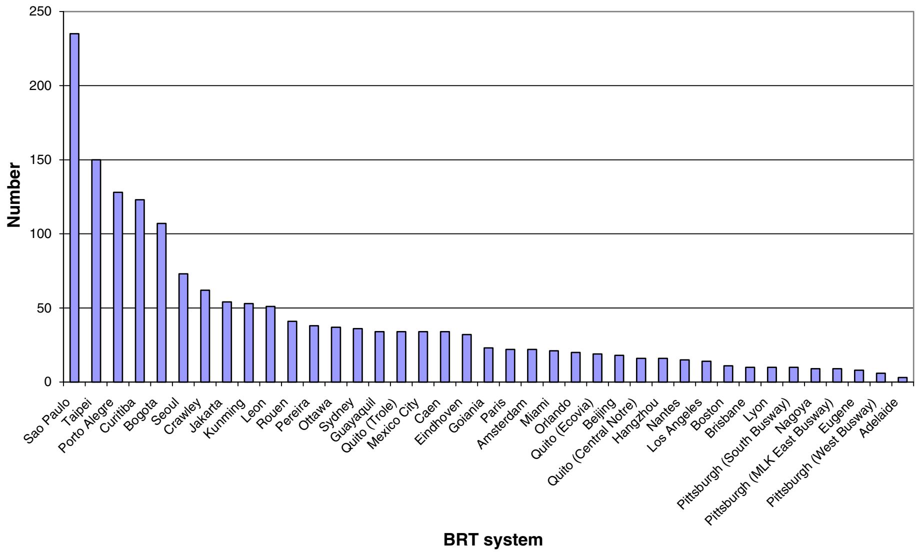

Fig. 12 Number of stations (2006)

equal, the more stations we have, the greater the likelihood of improved access and egress time, regardless of how many buses actually stop at all stations or have express status. Reducing headways through increased frequency[9] is clearly an important influence on

[9] Tom Wilson has pointed out that both enthusiasts and professionals in public transport often use "maximum" and "minimum" jointly with "frequency" and "headway" without thinking about what they really mean. In the case of very high frequency services, "frequency (or services) per hour" is a better concept.

Table 2 Passenger trips per day regression model

Explanatory variable	Estimated parameter	t-value
Number of stations	0.0098	4.68
Peak headway	−0.1681	−3.36
Trunk vehicle capacity	0.0052	1.97
Average fare per trip	−0.2577	1.92
Constant	7.9209	16.1
Adjusted R^2	0.659	
Sample size	37	

Dependent variable: natural logarithm of systemwide passenger trips per day per km

ridership[10] which reduces waiting time and in-vehicle time (through a lower dwelling time).

As expected there is a negative relationship for fares, with an implied direct mean fare elasticity of −0.12. The available carrying capacity of buses has a positive influence on ridership.

Conclusions

This paper has taken a closer look at the cost of constructing the BRT infrastructure for 44 systems and the range of design and service specifications that are offered through BRT in serving the public transport market. Given the widely varying specifications, the question of what might be the possible reason(s) for such varying costs begs some response. In general, the great majority of systems with all manner of variation cost less than $US10m per kilometre, and what is most notable about this is that these systems are not all confined to economies with relatively low input costs (especially labour) but are spread throughout developed and developing nations (such as USA, UK, Australia, Canada, France, Mexico, Korea, Brazil, and China).

In seeking out any possible sources of explanation, implementing a two stage multi-variate statistical analysis that can accommodate the differing scales of a range of descriptors of each system, we were only able to identify a few influences, other than some associative ones, that cannot be claimed to be causally defining sources of systematic variation in infrastructure costs. This is surprising as well as being an important finding. It signals, with the exception of the number of terminals and intersection treatment by signal priority or at grade separation, that there are no other features that we can identify that have a statistically significant impact on infrastructure costs per kilometre. One interpretation of this finding is that the data may be limiting. Alternatively, we are inclined to suggest that the differences are principally attributable to the context in which the costs were negotiated, including the number of bidders at the time where a franchised arrangement was in place, how the project was actually financed, the specific year in which the project as constructed (although all costs were converted to $US2006), and the extent to which there were major works such a bridges and tunnels.

In addition we have established further evidence to support the position that growing public transport patronage requires a system that recognises the important role that

[10] The Thredbo 10 conference in August 2007 concluded that frequency and reliability are increasingly becoming the major contributors to evidential growth in public transport bus patronage in many parts of the world.

interpretations of connectivity and frequency play. BRT systems appear to be focussing in the right place in growing public transport patronage.

Finally, we make a plea for continuing efforts to improve the quality of data, especially given that BRT is growing in popularity, and hence the benefits that can be gained in guidelines linked to scientifically rigorous empirical assessment of the expanding number of systems throughout the world.

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Appendix

Table A1 Candidate variables

Description	Units
Segregated busways for bus-only roadways	nominal
Existence of an integrated "network" of routes and corridors	nominal
Enhanced station environment (i.e., not just a bus shelter)	nominal
Special stations and terminals to facilitate transfers	nominal
Overtaking lanes at stations/Provision of express sevices	nominal
Improvements to nearby public space	nominal
High average commercial speeds (>20 km/h)	nominal
Actual peak ridership over 8,000 passengers per hour per direction	nominal
Pre-board fare collection and fare verification	nominal
At-level boarding and alighting	nominal
Fare- and physical -integration between routes and feeder services	nominal
Entry to system restricted to prescribed operators under a reformed business and administrative structure (closed system)	nominal
Competitively-bid and transparent contracts and concessions	nominal
No need for operational subsidies	nominal
Independently operated and managed fare collection system	nominal
Quality control oversight from an independent entity/agency	nominal
Low-emission vehicle technology (Euro III or higher)	nominal
Automated fare collection and fare verification system	nominal
System management through centralised control centre, utilising automatic vehicle location system	nominal
Signal priority or grade separation at intersections	nominal
Distinctive marketing identity for system	nominal
High-quality customer information (e.g., clear maps, signage, real-time information displays)	nominal
Modal integration at stations (e.g., bicycle parking, taxi stations, easy transfers between public transport systems)	nominal
Supporting car-restriction measures (e.g., road pricing)	nominal
Year system commenced	year
Number of existing trunk corridors	number
Total length of existing trunk corridors (km)	km
Number of trunk routes	number

Table A1 continued

Description	Units
Location of busway lanes	nominal
Location of doorways	nominal
Type of surface material on runways	nominal
Type of surface material on runways at stations	nominal
Total length of existing feeder routes (km)	km
Projected length of total future trunk corridors (km)	km
Number of stations	number
Average distance between stations (m)	m
Number of stations with passing lanes	number
Number of terminals	number
Number of depots	number
Number of total system passengers-trips per day	number
Actual peak ridership (passengers per hour per direction)	psg/hr per direction
Actual non-peak ridership (passengers per hour per direction)	psg/hr per direction
Average commercial speed (kph)	(kph)
Average peak headway (minutes)	(minute)
Average non-peak headway (minutes)	(minute)
Average dwell time at stations (seconds)	(second)
Number of trunk vehicles	number
Trunk vehicle type	nominal
Fuel type used in trunk vehicles	nominal
Trunk vehicle capacity	passengers per vehicle
Trunk vehicle length (m)	m
Number of feeder vehicles	number
Type of guidance system, if applicable	nominal
Type of fare collection/verification technology	nominal
Number of intersections with priority signal control	number
Number of grade-separated intersections	number
Fare (US$)	US$
Total planning costs (US$)	US$
Average trunk vehicle costs (US$)	US$
Total infrastructure costs (US$ per km)	(million US$/km)

Given that many, but not all, of the candidate influences are nominally scale variables (such as shown in Figures in the text as yes, no, partial, etc.), a technique known as nonlinear canonical correlation analysis (NLCCA) was proposed as a way of considering the best way of scaling the range of levels. The first stage uses NLCCA as a way of quantifying mixtures of nominal, ordinal, and ratio scaled variables all at once, while determining the strength of the relationship between each optimally quantified variable and the (one, in this case) dependent variable. Given the small sample size (in terms of low category frequencies) and missing data, we had to progressively work through subsets of potential explanatory variables.

A solution to the nonlinear CCA problem was first proposed by Gifi (1981), De Leeuw (1985), Van der Burg and De Leeuw (1983). The method simultaneously determines both

Table A2 The NLCCA results used to establish the candidate levels of potential explanatory variables

Explanatory variable	Optimal scale of explanatory variables versus dependent variable				All optimally scaled variables	
	Else (1)	Partial (2)	Yes (3)	Monotonic?	Estimated parameter	*t*-value
Average commercial speed >20 kph	dichotomous				0.562	3.72
At-level boarding and alighting	−1.034	−0.404	1.127	yes	−0.678	−4.61
Entry restricted to prescribed operators	−2.517	−1.063	0.473	yes	0.529	3.74
No need for operating subsidies	0.458	−1.819	1.371	no	−0.511	−3.74
Independently operated and managed fare system	dichotomous				0.462	2.49
Signal priority or grade separation at intersections	−1.136	1.415	0.753	no	0.670	4.22
Constant					1.420	11.64
Adjusted R^2					0.720	
Sample size					35	

Dependent variable: natural logarithm of infrastructure cost ($USm per kilometre)

optimal re-scaling of the nominal and ordinal variables and explanatory variable weights, such that the linear combination of the weighted re-scaled variables in one set has the maximum possible correlation with the linear combination of weighted re-scaled variables in the second set. Both the variable weights and optimal category scores are determined by minimising a loss function derived from the concept of "meet" in lattice theory (see Gifi 1990). A nonlinear CCA solution involves, for each canonical variate, weights for all the variables, optimal category scores for all ordinal and nominal variables, and a canonical correlation.

After NLCCA identifies which variables are statistically significant, and how their categories score, we can do one of two things as stage 2: use the variables in terms of their new rescored scales, or break them into dummy coded (1,0) variables. The optimal scores often show that some categories can be combined. Although this can be explored from the outset through dummy variables (e.g., testing 'yes' and 'partial' separately and combined), the dummy variable approach results in more variables, and the effect of a single nominal variable (here both 'yes' and 'partial') is sometimes spread into two variables. Without NLCCA, in order to test all categories of all nominal variables, one would have more than 40 dummy variables (and, given missing values, a sample size much lower). Clearly this is too many variables. Using the new scales obtained with NLCCA is more elegant in terms of measuring the total effect of a single multi-category nominal variable. Importantly, even if one adopts a dummy variable specification as the final model, the guidance offered through NLCCA[11] is substantial in reducing the problem to a workable size.[12]

[11] Optimal scales have a specific advantage over the dummy variable specification. If one uses multiple dummies from the same nominal variable, they will naturally be highly (negatively) correlated. In forecasting the effects of a change in categories, the analyst may have to decrease one category while simultaneously increasing the other.

[12] When we initially adopted a dummy variable specification without the insights from NLCAA, we obtained, after extensive estimation, very few statistically significant effects. When we used NLCCA as the guiding framework, the selection of final statistically significant dummy variables was immediate as well as producing a much better model in terms of explanatory power.

Table A3 Dummy coded multivariate regression

Explanatory variable	Estimated parameter	*t*-value
High average commercial speeds >20 kph for yes and partial (1,0)	0.9957	3.92
At-level boarding and alighting yes (1,0)	−1.1450	−3.48
At-level boarding and alighting partial (1,0)	−0.6562	−2.12
Entry restricted to prescribed operators yes (1,0)	1.115	3.17
No need for operating subsidies yes (1,0)	−1.2027	−5.82
Independently operated and managed fare system yes (1,0)	1.029	3.90
Signal priority or grade separation at intersections yes (1,0)	1.0876	3.68
Signal priority or grade separation at intersections partial (1,0)	1.6728	6.65
Boston BRT (1,0)	1.1213	3.94
Nagoya BRT (1,0)	0.9867	3.47
Pittsburgh West BRT (1,0)	1.2661	4.99
Constant	−0.3459	−1.10
Adjusted R^2	0.742	
Sample size	35	

Dependent variable: natural logarithm of infrastructure cost ($USm per kilometre)

We present the NLCCA results in Table A2 and used this as the basis of selecting the appropriate dummy variable specification for traditional multivariate regression estimation (Table A2) for inclusion with ratio scaled variables. In Table A2, the categories of the nominal variables are optimal in that the resulting variables provide the best linear combination that explains the optimally recoded ordinal dependent variable. It is a closed-form eigenvalue least squares solution. We then use the rescaled variables in ordinary (log-linear) regression.

We can clearly see that there are some very influential design and service delivery features that are linked to the costs of infrastructure, some of them being strictly associative such as operating subsidy, the presence of an independently operated and managed fare system, and entry restricted to prescribed operators. In one sense, these variables are beneficiaries of a particular infrastructure design that limits the number of operators, is designed to support efficient operators who do not require operating subsidy, and has a separate supplier of the managed fare system. Of particular note is the positive parameter estimate for operator entry, suggesting that systems with fewer operators (in many cases a single operator selected by competitive tendering or negotiated performance-based contracting) tend to be those that have more expensive infrastructure per kilometre.

Three design elements have an upward effect on infrastructure costs and two have a downward impact. Higher commercial speeds above 20 kph where this is always the case or partially the case, and signal priority or grade separation at intersections (distinguishing always and partially), result in substantially higher infrastructure costs per kilometre (noting that the dependent variable is a natural logarithmic transformation). At-level boarding and alighting, where it is the only facility in place or where it is partially provided, has a strong downward impact on infrastructure costs.

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