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Bus rapid transit systems: a comparative assessment

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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.

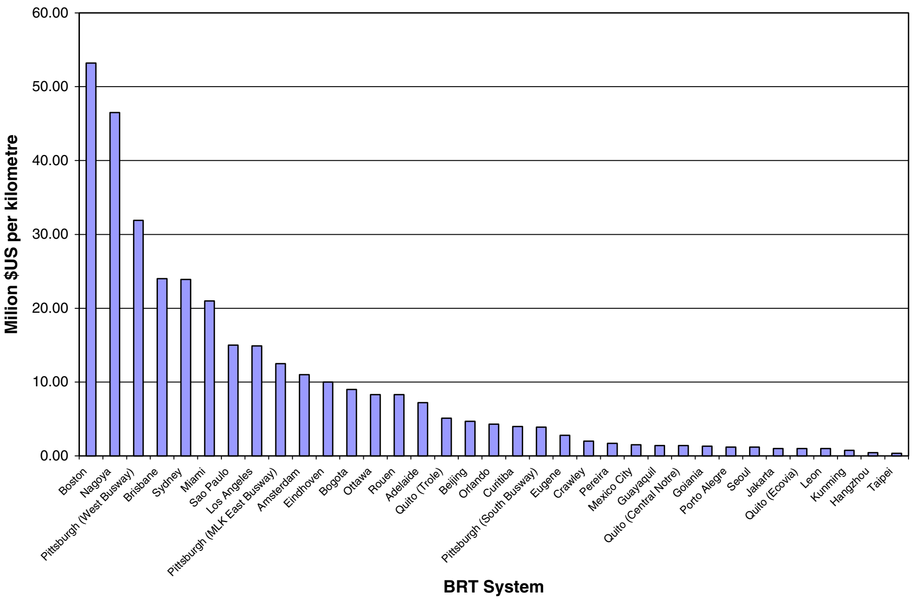

Fig. 1 Total infrastructure costs per kilometre ($m2006)

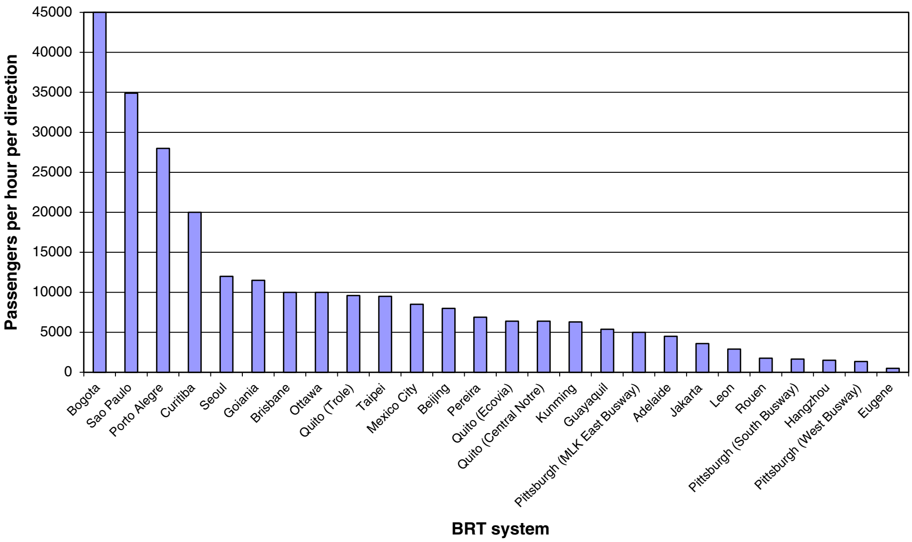

Fig. 2 Peak ridership (2006)

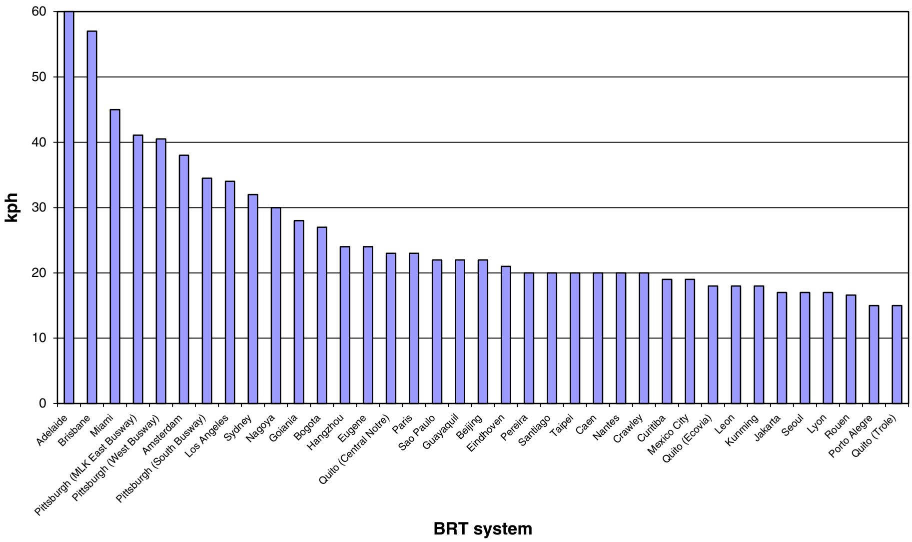

Fig. 3 Average all day commercial speed (various years in 2000–2006)

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

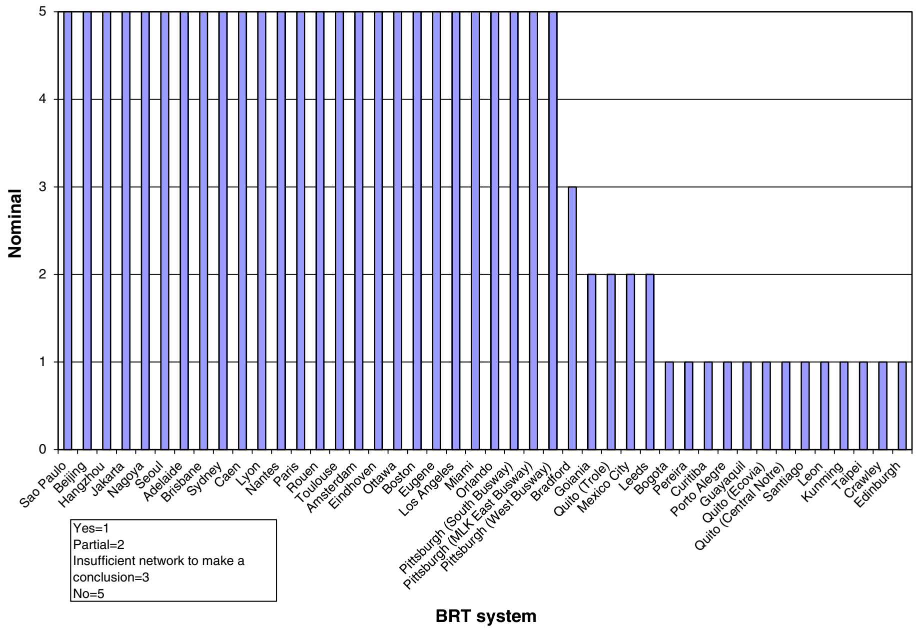

Fig. 4 No need for operational subsidies (2006)

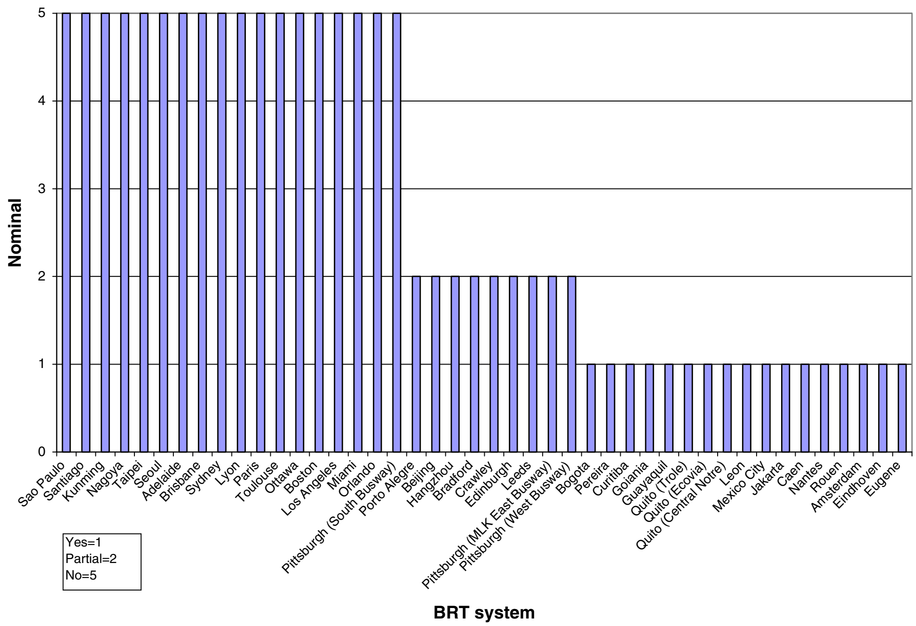

Fig. 5 At-level boarding and alighting (2006)

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

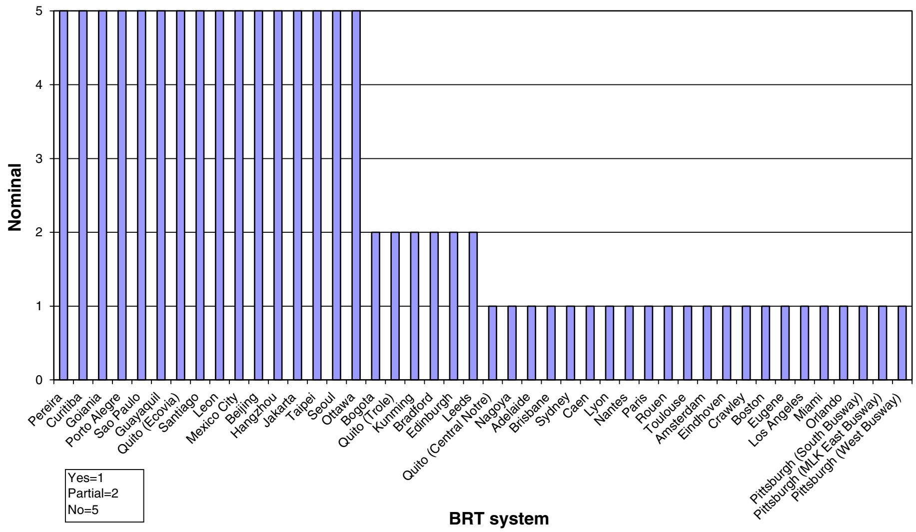

Fig. 6 Signal priority or grade separation at intersections (2006)

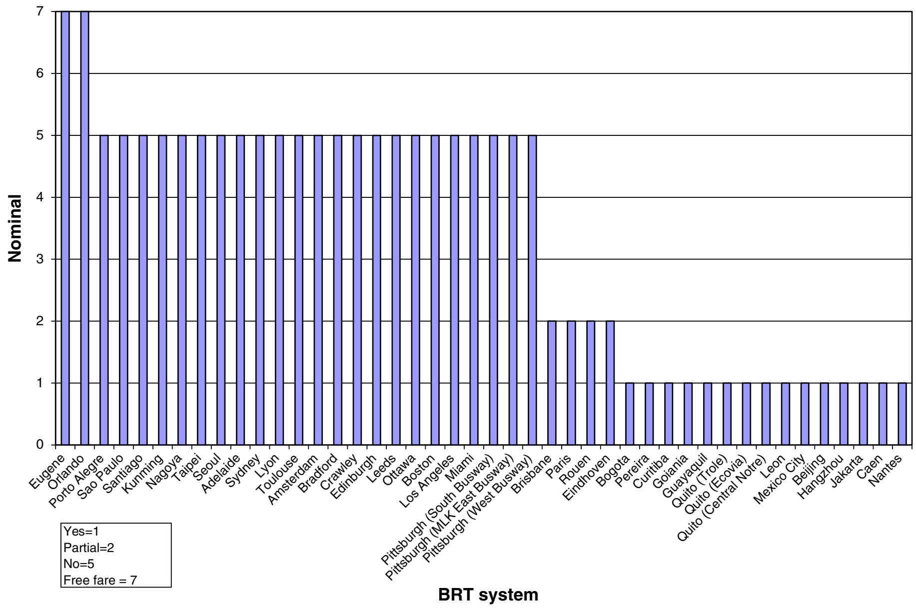

Fig. 7 Pre-board fare collection and fare verification (2006)

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.

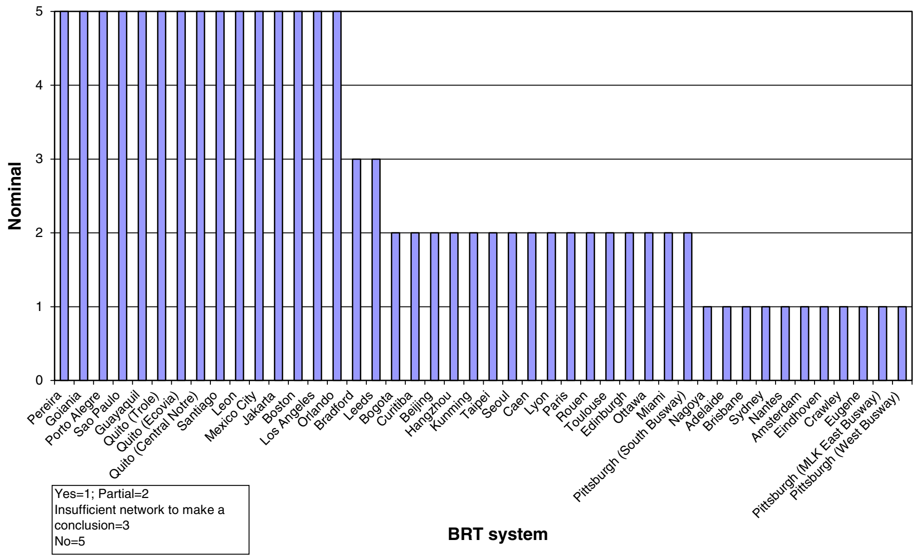

Fig. 8 Modal integration at stations (2006)

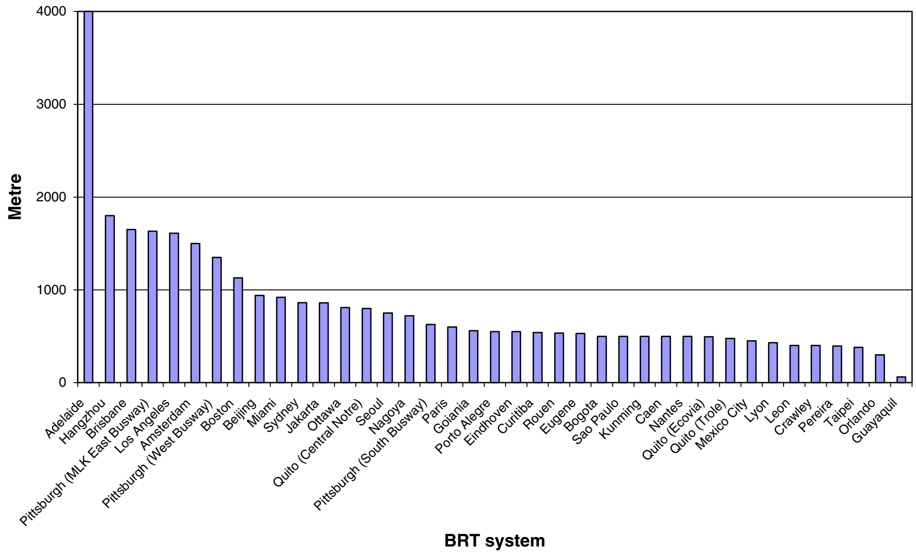

Fig. 9 Average distance between stations (2006)

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.

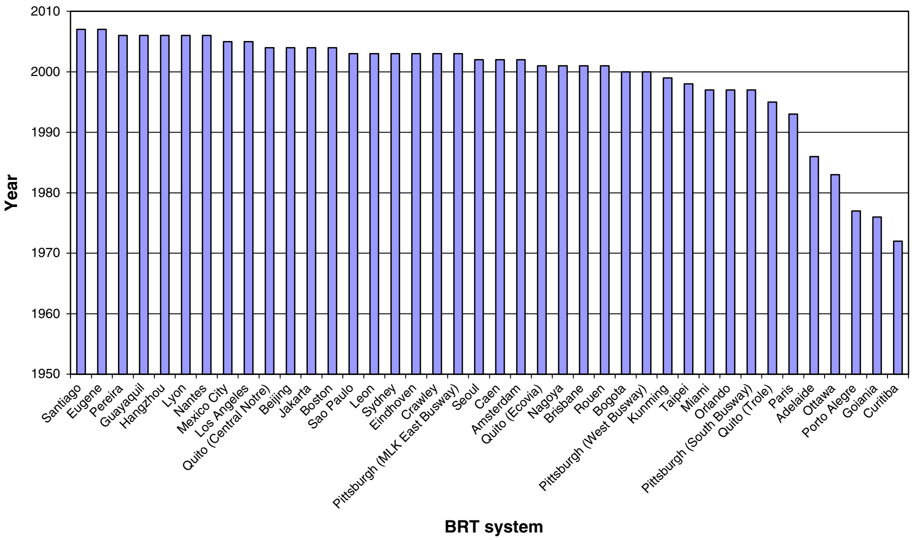

Fig. 10 Age profile of BRT systems (2006)

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.

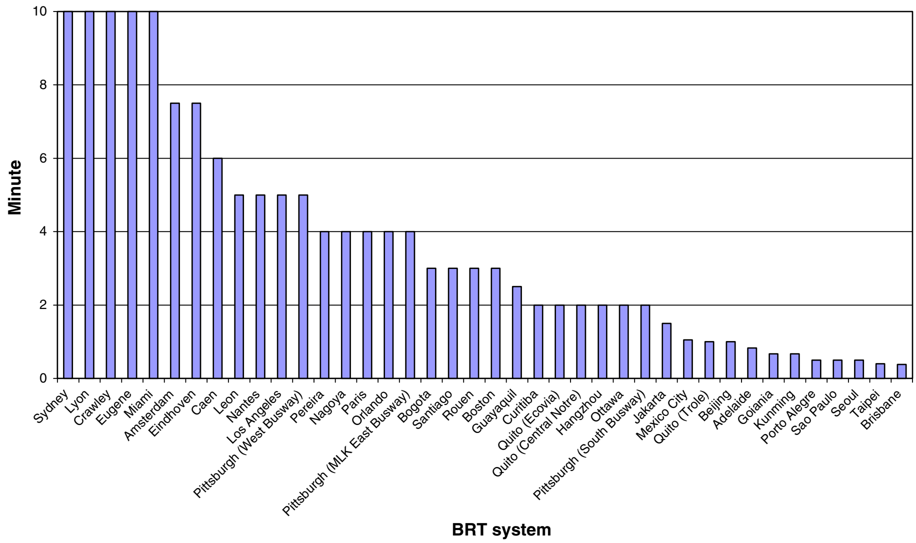

Fig. 11 Average peak headway (2006)

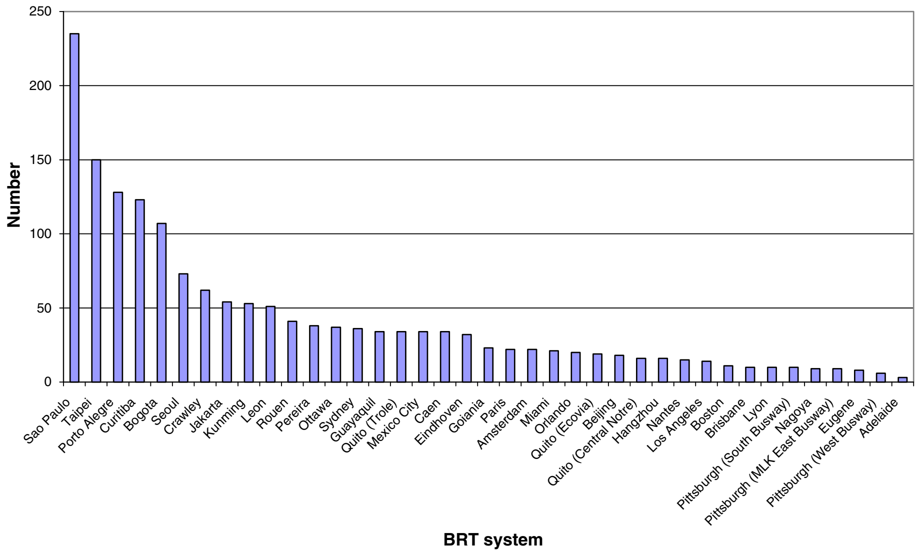

Fig. 12 Number of stations (2006)

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 multivariate 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.

Acknowledgement The contribution of Zheng Li in assisting in preparing the data is acknowledged as is the ongoing discussions with Lee Schipper. Detailed comments from Tom Wilson (Department of Transport, Energy and Infrastructure Adelaide) and Alejandro Tirachini (ITLS and University of Chile) and four referees are appreciated.

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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