Comparative Evaluation of Alternate Bus Rapid Transit System (BRTS) Planning, Operation and Design Options

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Abstract: A comparative evaluation examines alternate planning, operational and design options for Bus Rapid Transit Systems. Quantified performance results for different indicators for various planning and design configurations are generated using a spreadsheet tool. Sixteen theoretical configurations, two standard designs in varying contexts and two currently operational design variations are compared. Results show that bus operational speeds in open systems are approximately 25% less than those in closed systems. However, high operational speeds do not help offset passenger transfer delays for short trips. Open systems provide higher passenger speeds than closed bus operations for trip length less than 10km. Restricting peak bus speed to less than 40km/h for safety considerations does not hamper passenger or operational performance.

Keywords: BRTS, Performance Evaluation, Model, Performance Indicators, Design, Planning

1 BACKGROUND

Bus Rapid Transit System (BRTS) is a bus based transit system which allows higher speed, improved capacity and better bus safety by segregating buses from other roadway traffic into a separated bus way (Levinson et al. 2003). Figure 1 shows a section of Delhi BRTS with central segregated lanes reserved for buses and emergency vehicles. As more and more cities opt for BRTS, several different design and operational strategies addressing varying local needs and context have emerged (Tiwari and Jain 2010). More than 137 cities in the world now operate BRTS corridors (Anon 2012). No two systems are identical; their characteristics vary. A BRTS is custom built to the needs of the city. However by addressing local concerns and requirements, choices of design features are made that amount to certain degree of compromise or deviation from best options. Discussions remain on the definition and composition of a ‘best’ option and on the quantification of performance loss incurred in compromises made.

A number of software and tools exist which allow quantification of BRTS performance based on inputs provided and also include a feature or indicator based rating system which allows an overall evaluation of performance (Hook et al. 2012;Institute for Transportation and Development Policy 2011;S G Architects and Fazio Engineerware 2013). Measurable indicator-based system performance values and benchmarks allow evaluation of planning and design benefits. Weighting the performance of the system against different measures provides an overall rating. Each evaluation tool uses its own defined mixture of such indicators. However comparison of case study evaluation results by these tools show significant difference in assessment of performance (Gandhi 2013;Weinstock et al. 2011). This difference is attributed to difference in indicators used as well as difference in evaluation methodologies (Gandhi 2013). Some tools (Institute for Transportation and Development Policy 2011) do not relate to design and planning elements such as different station, intersections, lane types and their configurations. Some either exclude indicators other than operator specific indicators or include such indicators as only qualitative and not quantitative indicators (Hook et al. 2012).

For example, an evaluation (Hook et al. 2012) provides very high rating for barrier controlled off-board ticketing at BRTS stations because it minimizes fare evasion; it helps in data collection, and multiple routes are accommodated using the same infrastructure. While the scorecard identifies positive impact on bus operations and system management, the overall negative impact due to delays and queues at turnstile for passengers is not recognized or evaluated. One reason for this could be that operator specific data is easy to collect and available in abundance, whereas as passenger specific data such as walk distances, delays and journey time are difficult and expensive to collect. Thus, many such standards are based on observable system characteristics and not any quantifiable data (Hook et al. 2012). User indicators play a prominent role in determining whether a system is used and thus deserve careful attention while planning, designing or evaluating a system.

The solution lies in the ability to predict the performance of a BRTS system based on its planning and design details. One could then evaluate results against a list of key identified indicators. This paper reviews and compares various BRTS system designs. The evaluation will use a spreadsheet tool to model and quantify performance of different BRTS design alternatives against identified indicators. The results are then compared against current assumptions and theories around what comprises an ‘ideal’ BRTS.

FIGURE 1 BRTS Corridor in Delhi

2 LITERATURE REVIEW – BRTS PLANNING AND DESIGN INDICATORS

Pratt and Lomax (1996) have proposed a set of indicators based on the objectives of the bus based public transport system that professionals desire to evaluate. Though these indicators tend to be specific to the end use of the measures, there are often debates whether multiple indicators or a single indicator is useful in evaluation. For example, maximized ridership within an allowable deficit unit may be used as a measure of transit performance (Talley and Becker 1982). Similarly, other single measures include cost per passenger or per passenger mile (Nash 1978;Patton 1983). However, performance measures may respond to different intended recipients of benefits of the system or may respond to the objectives of various "publics" (Fielding et al. 1985).

Different measures use different sets of indicators. This is also dependent on its end use and the availability of data types used in evaluation. One should primarily base indicator selection on the end use of bus performance measures. Selection of indicators is often based on the availability of measurable or observable data (Hook et al. 2012). A wide gap frequently exists between end use and data availability to assess performance because either relevant data are not observable or is too expensive or difficult to collect (Hook et al. 2012). Thus, developers of performance measures often use proxy indicators. Since many measures use proxy indicators (Hook et al. 2012), because they are cost effective, there efficiency in replacing appropriate direct indicators remain open to evaluation and debates.

Two types of data exist, objective and subjective (Institute for Transportation and Development Policy 2011). Objective data has two sources. One source involves data collection devices, i.e., recorded data (Mulley et al. 1998), and the other source comes from validated model usages (S G Architects and Fazio Engineerware 2012a). Analysts primarily use recorded data in operational studies. Most bus operational studies use generated data from ticketing devices, fare collection devices and speedometers. Since an abundance of recorded data exists in bus operational studies, one directs most bus benchmarking efforts towards the benchmarking of operational performance. Subjective data uses bus user and societal derived indicators that are often either proxy to operational indicators or qualitative in nature, creating doubts on the accuracy of such measures.

To overcome these deficiencies in performance evaluation of bus based public transport systems, a spreadsheet based modelling tool (S G Architects and Fazio Engineerware 2013) has been developed. This tool provides quantitative assessment of bus performance against multiple indicators (Gandhi 2013). These indicators respond to the requirements of three stakeholders in a public transport system. These are the society, passenger and the operator (Agarwal 2011). The tool has two main components. One of these is the modelling engine which predicts performance in terms of commercial speed, passenger speed, capacity, etc. and uses design, planning and context related inputs such as operation type, station type, average trip length etc. The outputs of the modelling engine include prediction of commercial speed, passenger speed, journey time, capacity, etc. Second component is the evaluation framework. Outputs generated by the modelling engine are used as inputs in the evaluation framework (S G Architects and Fazio Engineerware 2012b). Here performance against ten critical indicators is evaluated and aggregated in to an overall performance score. Aggregation is based on individual indicator weights assigned using inputs from different stakeholders representing passengers, civil society organizations (CSOs), operators and experts in public as well urban transport. These indicators and their categories have been listed below (Gandhi 2013).

1. Social Indicators
    - Peak Bus Speeds (due to its impact on fatal crashes)
    - Potential for Shift from Private Transport – based on passenger travel time comparison between buses (in BRTS) and private vehicles.
    - Potential for retaining existing public transport demand by improving the performance of current bus system.
    - Allowing universal access and barrier free mobility for primarily in terms of disabled friendly infrastructure and fleet.
2. Passenger Indicators
    - Passenger speed or door to door travel time
    - Total walk distance for passengers in a one way trip

  - Total delay to a unit passenger in a one way trip
3. Operational Indicators
   - Expected system capacity
   - Expected Operational or commercial speed (Km/h)
   - Average per station and junction delay to a unit bus in the BRTS

3 METHODOLOGY

A spreadsheet tool (S G Architects and Fazio Engineerware 2012a) is selected to model BRTS design configurations. The tool is based on standard motion equations (Vuchic 2005) while default values and weights for indicators used in the tool are based on primary surveys (Gandhi 2013;S G Architects and Fazio Engineerware 2012b). The tool produced the necessary results against performance indicators in each category, and, most importantly was validated on three BRTS systems namely Ahmedabad, Bogota and Delhi with 94 to 99% accuracy (S G Architects and Fazio Engineerware 2012c).

Quantified performance results for different indicators against various BRTS planning and design configurations are generated. The comparisons of quantified results for deviations from these configurations through variations in critical design and planning components reveal their impact on the overall performance. One can perform the comparisons in three stages:

1. Comparative analysis of sixteen theoretical design alternatives
2. Comparative analysis of two design alternatives in varying traffic conditions
3. Comparative analysis of two existing BRT systems

3.1 Design Feature Inputs of Sixteen Theoretical Alternatives

In the first stage, BRTS designs vary only by bus station and operation type with all other parameters kept common. Sixteen configurations shown in Table 2 are selected using two operation types, i.e., ‘open’ and ‘closed’ and eight bus station types. An ‘open’ system occurs when bus operations allow more than one route to use BRTS corridors, i.e., buses join and leave the corridor at different intersections. A ‘closed’ system refers to bus operations where a single route uses the corridor from end to end and no other route or bus enters the dedicated bus lanes. Bus station types are ‘island or staggered station’, ‘midblock or junction station’ and ‘with or without bus overtaking lane at the station’ as shown in Figure 2. Staggered stations are stations dedicated to or serving only one direction bus movement. Two stations are provided at each location for two different direction of bus movement and are located on either side of the bus lanes. Island stations are stations dedicated to or serving both directions of bus movement along the two longitudinal edges of the station and are located between the two bus lanes. If the distance of an intersection is less than or equal to 80m from station entrance and the junction is a signalized junction or roundabout, then it is considered ‘Junction.’ If an intersection is greater than 80m from station entrance, it is ‘Midblock.’ Overtaking lanes within segregated bus lanes allow buses to pass or turn at stations. Systems with staggered station with overtaking lanes imply that additional bus overtaking lanes are provided at both station and at the near side of intersections. Similarly, 'without overtaking lanes' means that no additional bus lanes are provided either at stations or at near side of intersections.

FIGURE 2 Conceptual sketches showing different BRTS station configurations along central segregated bus lanes

'Base design features' in all alternates are included to represent current conditions in most Indian cities (Tiwari and Jain 2010). These included average trip length of 7km, high density mixed land use, a demand of 7500 passengers per hour per direction (PPHPD), walking speed of 1 m/s, average bus acceleration and deceleration of 1 m/s^2 each, average spacing between stations as 600m, four arm signalized junctions with corridor being the major road while cross road is minor road, all vehicular turns allowed at all junctions, first boarding bay, last for far side direction, 26m away from stop line, near side stations for staggered stations, central segregated bus lanes, on board ticketing, single station entry, 150 second signal cycle at vehicular intersections, 60 second signal cycle at pedestrian crossings at midblock stations, no bus priority signal, no dedicated pedestrian phase at intersections, at grade signalized pedestrian crossing access to stations, use of low floor urban bus fleet and 30% turning buses in an open system, with 5 different routes. These are a few of the 133 variables (S G Architects and Fazio Engineerware 2012c) input in the tool for analysis. Table 1 shows the sixteen possible alternatives of BRTS configurations.

Comparisons of these sixteen different station and operational design combinations use societal, passenger and operational indicators by varying one of four design elements at a time as shown in Figure 3. These design elements and the limits of their variations are:

- Average distance between stations in the BRTS corridor – varying between 400 to 1000m
- Bus Passenger demand in the corridor – varying between 2500 and 25000 PPHPD
- Distance of first boarding bay from the stop line – varying between 0 to 78m
- Signal Cycle length at junction – Varying between 120 to 300 seconds

3.2 Design Feature Inputs of Two BRTS Design Alternatives in Varying Traffic

In the second stage, two design alternatives were: (1) island stations in closed system set back by 60m from the stop line and (2) staggered near side stations in an open system set back by 26m from the stop line. The alternatives are evaluated for their performance in varying contexts under controlled conditions keeping all other design parameters constant, i.e., both using signal cycles of 150 seconds, both without overtaking lanes and same number of boarding bays.

The impact of varying context such as peak bus speeds, average trip length and average speed of vehicles in general traffic lanes in the corridor; on passenger door-to-door journey time, passenger speed and commercial speed has been evaluated for the two design alternatives. In the evaluations, peak bus speed ranged between 40 and 100km/h, average spacing between stations ranged between 500 to 1000m, average trip length varied between 4 to 16km and average motor vehicle speeds varied between 10 to 30 km/h.

3.3 Design Feature Inputs of Two Existing BRT Systems

In the third stage, the comparative analysis involved two existing BRTS. Ahmedabad and Delhi BRTS in India have adopted different operations and design features. The design adopted by Delhi includes open bus operations with staggered near side parallel stations with overtaking lanes with the use of a primarily low floor bus fleet. Staggered near side parallel station refer to a configuration of bus stations where two parallel stations with a bus boarding lane each is provided for each direction of bus movement on either side of an intersection (Figure 2). Ahmedabad adopted a closed bus operation model with high floor island stations along with high floor buses. These two existing BRTS represent the base case in comparative analyses.

The evaluation of two design alternatives for Ahmedabad BRTS involved: (1) changing the station to staggered near side with overtaking lanes while keeping operations closed, and (2) changing the station to staggered near side with overtaking lanes and changing bus operations to an open system. Evaluation of two design alternatives for Delhi BRTS involved: (1) changing the station to island without overtaking while keeping the operations as open, and (2) changing the stations to island without overtaking and changing the bus operations to closed system. For Delhi BRTS design, a proposed improvement using an alternate signal cycle at intersections is also modeled as an alternative design. The existing base case retains all other contextual parameters and other features such as type of commuter access to stations.

The existing base case of each city is different from the other city. Table 1 presents these differences and similarities.

TABLE 1 Comparison of city profile and features of Ahmedabad and Delhi BRTS corridor (Centre for Environmental Planning and Technology 2007;Centre for Science and Environment 2011;Tiwari and Jain 2010;Velmurugan et al. 2012).

S. No.	Feature	Ahmedabad	Delhi
1	Average Trip Length (km)	5.3 to 8.1	10
2	Corridor length (km)	17.2 (RTO to Kankaria Lake)	5.8
3	Corridor location in city	Periphery	Passing through city centre
4	Corridor right of way (ROW) (m)	60	45 to 52
5	Traffic Volume in Passenger Car Unit (PCU) per (peak) hour per direction	7350	15639
6	Average Motor Vehicle speed (km/h)	24	14 to 15

4 RESULTS

4.1 Comparative Analysis of Sixteen theoretical alternatives

Table 2 shows pertinent results of comparative analyses using ‘base design features’ and involving the sixteen BRTS alternatives. Under operational indicator capacity, one records results for commercial speed and capacity in the BRTS alternatives. Under passenger indicator capacity the results are recorded for door to door journey time, access with egress time and total walking distance in a one way trip.

TABLE 2 Performance measures of sixteen different BRTS design alternatives

ID	Station Design				Performance Measure				
	Open or Closed Op.	Junction or Mid-block	Island or Stagger	With or without overtaking bus lane	Com. Speed in km/h	Freq. (buses per hour per dir.)	Travel Time (min)	Access + Egress Time (min)	Total Walk dist. in m
1	Open	Junction	Staggered	With Overtaking	17.2	264	45.2	20.1	1008
2	Open	Junction	Staggered	Without Overtaking	15.2	72	46.4	19.8	1002
3	Open	Junction	Island	With Overtaking	17.0	216	45.5	20.1	1015
4	Open	Junction	Island	Without Overtaking	15.0	72	46.7	19.8	1009
5	Open	Mid Block	Staggered	With Overtaking	19.0	360	43.9	30.7	1186
6	Open	Mid Block	Staggered	Without Overtaking	14.9	72	47.7	30.8	1180
7	Open	Mid Block	Island	With Overtaking	19.1	360	44.0	30.9	1193
8	Open	Mid Block	Island	Without Overtaking	14.5	72	48.3	30.9	1187
9	Closed	Junction	Staggered	With Overtaking	20.8	336	46.4	34.2	1262
10	Closed	Junction	Staggered	Without Overtaking	20.8	264	46.0	33.8	1250
11	Closed	Junction	Island	With Overtaking	20.5	264	46.5	34.2	1272
12	Closed	Junction	Island	Without Overtaking	20.5	192	46.2	33.8	1260
13	Closed	Mid Block	Staggered	With Overtaking	19.9	408	48.3	35.6	1610
14	Closed	Mid Block	Staggered	Without Overtaking	20.3	360	47.9	35.5	1598
15	Closed	Mid Block	Island	With Overtaking	20.0	408	48.4	35.8	1620
16	Closed	Mid Block	Island	Without Overtaking	20.3	288	48.1	35.6	1620

Figure 3 shows the effect of varying average station spacing, station set back from stop line at intersection and signal cycle length on operational speed, passenger journey time and maximum frequency for staggered and island junction stations with overtaking lane and for open and closed bus operations. Each graph in Figure 3 presents the effect of one BRTS feature on the four variant, while keeping other base variants constant.

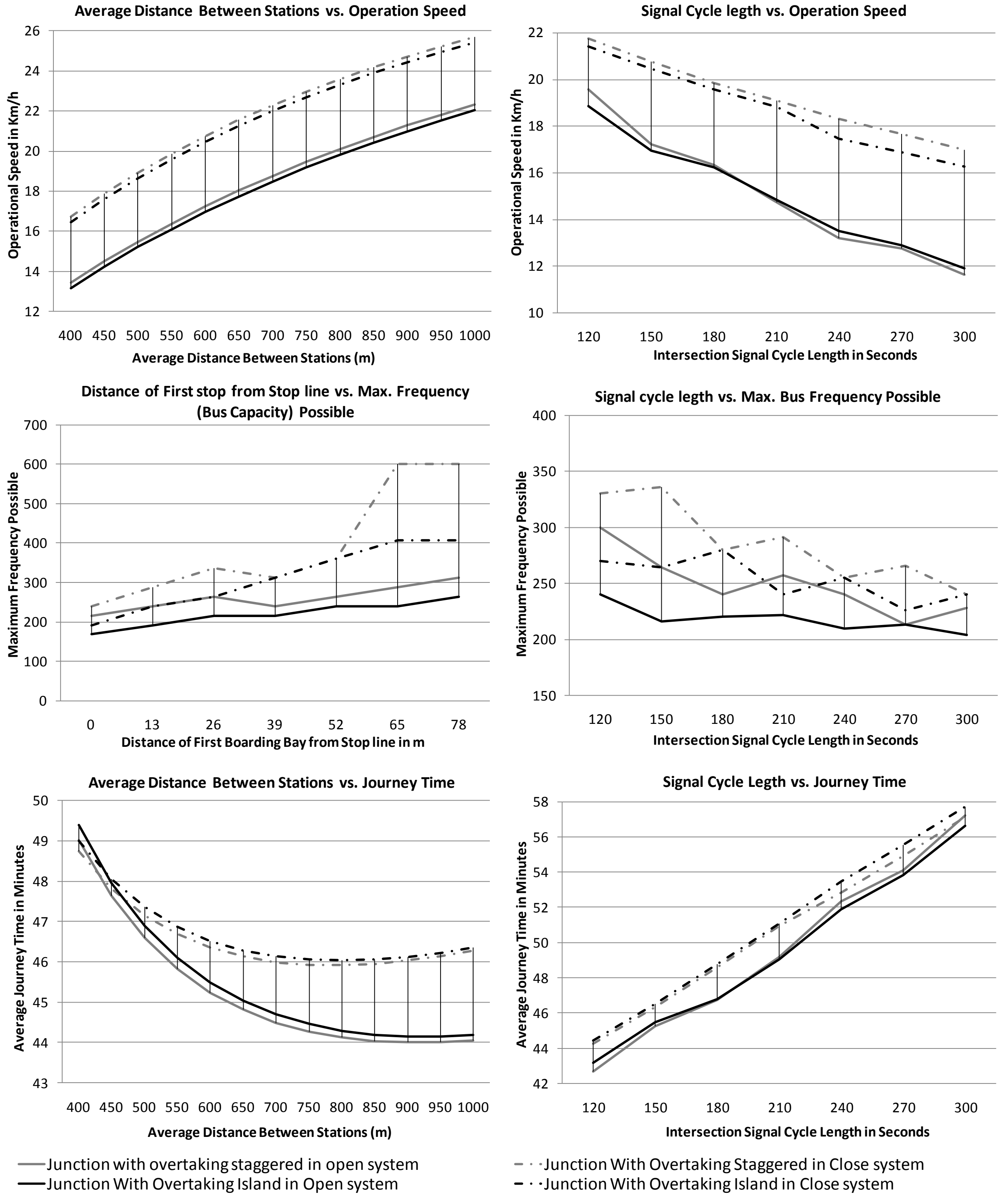

FIGURE 3 Impact of variation in single feature (from base condition) on performance of different BRTS variants

4.2 Comparative Analysis of Two BRTS Design Alternatives in Varying Traffic

Table 3 shows the effect of varying average station spacing and peak bus speed on journey time. Table 4 presents the effect on commercial speed. Table 5 presents the results on varying average trip length and average vehicular speed in the corridor. The results show the effect on passenger speed gain by BRTS over buses in mixed traffic condition under normal operations.

Table 3 Average journey time in minutes for 6 km and 10km trip length.

Peak Bus Speed in km/h	Average Distance Between Stations in m.											
	500		**600**		**700**		**800**		**900**		**1000**	
	6km	**10km**	**6km**	**10km**	**6km**	**10km**	**6km**	**10km**	**6km**	**10km**	**6km**	**10km**
40	44.1	58.3	43.5	56.6	43.3	55.6	43.3	55.0	43.5	54.7	43.8	54.7
50	43.5	54.7	42.8	55.1	42.5	54.0	42.5	53.4	42.7	53.1	43.0	53.0
60	43.2	56.4	42.5	54.4	42.1	53.2	42.1	52.5	42.2	52.1	42.5	52.0
70	43.2	56.2	42.3	54.1	42.0	52.8	41.9	52.0	42.0	51.6	42.2	51.4
80	43.2	56.2	42.3	54.0	41.9	52.6	41.8	51.7	41.8	51.2	42.1	51.0
90	43.4	56.4	42.4	54.0	41.9	52.5	41.7	51.6	41.8	51.1	42.0	50.8
100	43.6	56.7	42.5	54.2	42.0	52.6	41.8	51.6	41.8	51.0	42.0	50.7

Table 4 Commercial speed of BRTS buses in km/h, with closed operations.

Peak Bus Speed in km/h	Average Distance Between Stations in m					
	500	**600**	**700**	**800**	**900**	**1000**
40	18.6	20.5	22.0	23.3	24.4	25.4
50	19.8	22.1	24.0	25.6	27.1	28.4
60	20.5	23.1	25.3	27.3	29.0	30.6
70	20.9	23.6	26.1	28.3	30.3	32.2
80	21.0	23.9	26.6	29.0	31.2	33.3
90	21.0	24.0	26.8	29.4	31.8	34.0
100	20.8	24.0	26.9	29.6	32.1	34.4

Table 5 Passenger speed gain with BRTS over buses in mixed condition (regular operation) for open (O) and closed (C) bus operations (in km/h).

Trip length in Km	Average Speed of Motor Vehicles in the corridor in km/h																	
	10.0		**12.5**		**15.0**		**17.5**		**20.0**		**22.5**		**25.0**		**27.5**		**30.0**	
	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C
4	2.0	1.6	1.7	1.3	1.5	1.0	1.3	0.8	1.1	0.6	0.9	0.4	0.8	0.3	0.6	0.1	0.5	0.0
6	2.3	2.0	2.0	1.7	1.7	1.3	1.4	1.0	1.1	0.8	0.9	0.5	0.7	0.3	0.5	0.1	0.3	-0.1
8	2.8	2.7	2.3	2.3	1.9	1.9	1.6	1.5	1.2	1.1	0.9	0.8	0.6	0.5	0.3	0.2	0.1	0.0
10	3.4	3.6	2.8	3.1	2.3	2.6	1.8	2.1	1.3	1.6	0.9	1.2	0.5	0.8	0.1	0.5	-0.2	0.1
12	3.9	4.5	3.2	3.9	2.6	3.3	1.9	2.7	1.4	2.1	0.8	1.6	0.4	1.2	-0.1	0.7	-0.5	0.3
14	4.3	5.2	3.5	4.5	2.8	3.8	2.1	3.2	1.4	2.6	0.8	2.0	0.3	1.4	-0.3	0.9	-0.7	0.5
16	4.6	5.8	3.8	5.1	3.0	4.4	2.2	3.6	1.5	2.9	0.8	2.3	0.2	1.7	-0.4	1.1	-0.9	0.6

4.3 Comparative Analysis of Two Existing BRT Systems

The spreadsheet model generated results for design alternatives of two operational BRTS corridors. Table 6 presents comparisons with each social, operator and passenger indicator. Results replicated for current design in each city match well with current documented capacity and observed operational speed on (Tiwari and Jain 2010).

TABLE 6 Performance comparison of Ahmedabad as well Delhi BRTS current designs against station design and bus operation alternatives.

Indicators	Ahmedabad - RTO to Kankaria BRTS Corridor (8 km trip length)			Delhi - Ambedkar Nagar to Moolchand BRTS Corridor (10km trip length)			
	Current Design - Closed Operation with Island Stations	Closed Operations with Staggered Station	Open Operations with Staggered Stations	**Current Design -** Open Operation with Staggered parallel Stations	Open Operation with Staggered Parallel Stations - improved Signal design	Open Operation with Island Stations	Closed Operation with Island Stations
Passenger time saving by BRTS over private transport (min)	**-28.9**	-25.1	-23.8	**-20.9**	-17.2	-22.6	-25.0
Passenger time saving by BRTS over current public bus (min)	**7.8**	12.4	11.5	**16.8**	20.1	15.1	12.7
Passenger speed (km/h)	**9.4**	10.1	10.4	**9.8**	10.4	9.5	9.2
Total walk distance for passenger in a one way trip (m)	**1476**	1257	1044	**1150**	1150	1171	1671
BRTS Access cum Egress time (min)	**39.4**	35.8	23.1	**32.4**	29.0	38.0	46.7
BRTS In-vehicle time (min)	**12.3**	12.1	23.5	**28.7**	28.7	24.9	18.4
System Capacity (PPHPD)	**14400**	14400	21120	**23000**	26133	11413	18418
Commercial speed (km/h)	**23.2**	23.5	21.6	**18.6**	22.3	19.4	23.3
Average per station cum junction delay per bus (sec)	**46.8**	45.3	54.7	**53.9**	51.3	65.1	49.4

5 DISCUSSIONS

5.1 Comparative Analysis of Sixteen theoretical alternatives

All sixteen theoretical design alternatives had significant impact of feature variations such as average spacing between stations, passenger demand, i.e., bus frequency, signal cycle length at intersections and gap between bus station and intersection on system performance as can be observed from Table 2 and Figure 3. The results for every performance indicator follow.

5.1.1 Commercial Speed

Variations in station setback from stop line do not affect commercial speed of buses in BRTS. Salient findings on commercial speed variations against variations in other design features are:

Effect of Average Station Spacing Variations

- Commercial speed of buses in BRTS has a linear relationship with average spacing between stations for all station type and increases with increasing stations spacing.
- Effect is the lowest for 'Midblock island stations without overtaking lane in an open system' (11 to 19.5 km/h) while it is highest for 'Junction Staggered stations with or without overtaking lanes in a closed system'(16.7 to 25.7 km/h).
- Effect is generally higher for closed systems than for open system, and higher with staggered stations than with island stations.
- For open bus operations, operational speeds are higher with bus overtaking lanes at stations than without them.

Increase in operational speed with increase in station spacing is understandable as buses are able to cruise for longer distances and the total dwell time in a trip reduces. Increased delay experienced by turning buses at intersections, reduced cruising distance as the bus stops twice between junctions, and increased delay to buses due to stacking on the far side of island stations explains the lower average commercial speed of midblock island station without overtaking lane in an open system

Effect of Passenger Demand Variations

- Average operational speed of buses in a system drops by approximately 1 km/h for island stations in an open system and between 1 and 1.5km/h for island stations in a closed system with increasing passenger demand
- Effect shows no variations for staggered stations in an open system
- Effect fluctuates between ±0.4 km/h for staggered stations in a closed system.

The reduction in operational speed for island stations as against limited or no variations in staggered stations is explained by the characteristic of the station, which serves as a near side station for one direction and a far side station for the other direction of buses. Since the capacity of BRTS is based on the maximum throughput of buses possible in a signal cycle at an intersection, near side stations will not be affected by higher bus numbers whereas stacking at far side stations will increase delays (S G Architects and Fazio Engineerware 2012c). However, island stations generally are able to carry at most 22000 PPHPD. In staggered station without overtaking lanes, signal cycle design limits capacity. The staggered station is unable to handle demands higher than 20000 PPHPD.

Effect of Signal Cycle Length Variations

Bus operational speed in BRTS reduces with increasing signal cycle length. Increased delays for buses due to longer signal cycles explain the reduction in operational speed.

5.1.2 Frequency

In general, BRTS designs with mid-block station support higher bus frequencies, than those with junction stations. Stations provided with overtaking bus lanes support higher bus frequency than those without overtaking bus lanes. Station design, i.e., island or staggered, and operations type, i.e., open or closed, has little or no impact on its own on peak system frequency. Variations in average stations spacing and passenger demand does not affect maximum achievable frequency in BRTS. Results shown in Figure 3 on frequency variations of each BRTS alternative against variations in other design features are:

Effect of Signal Cycle Length Variations

- Increasing signal cycle length increases system capacity in BRTS with 'Junction Island station without overtaking lane in a closed system'. The maximum gain of approximately 100 buses per hour occurred when signal cycle length increased from 120 to 300 seconds.
- For all other alternatives, the capacity remains roughly the same or reduces (mainly for stations in open system) by between 80 and 160 buses per hour.

  An increase in signal cycle length increases the green phase allocation for buses, but reduces the number of signal cycles in an hour. An increase in green phase allows more buses to process or pass in a signal while it reduces the number of cycles or the multiples, which yield the maximum frequency possible. This means that depending on the quantum of increase in the signal cycle length maximum achievable frequency can increase or decrease, for junction stations with bus overtaking lanes.
- The optimum signal cycle for all designs to allow maximum capacity is between 120 and 180 seconds.

Higher cycle length result in reduced number of cycles in an hour, and since the station can only hold and process a limited number of buses in a cycle (which does not change with signal cycle length), its turnover in an hour reduces, reducing the capacity of the system.

Effect of Station Distance from Stop Line at Intersection Variations

- All except two station designs i.e. 'midblock staggered stations without overtaking lane in a closed system' and 'midblock island stations without overtaking lane in an open system' show sensitivity of frequency to distance of bus boarding bay from the stop line at a junction or at grade pedestrian crossing.
- All designs show improvement in bus frequency when distance increases from zero to 26m. Frequency increase is by about 60 to 120 buses.

Junction Island and junction staggered stations with overtaking lanes in a closed system, show continuous increase in bus capacity with increase in this gap until 65m and no change beyond that.

5.1.3 Door to Door Journey Time

Salient findings on door-to-door journey time variations against variations in key design features are:

Effect of Average Station Spacing Variations

- Because the journey time for passengers is a sum of access and in vehicle time, the impact of increasing spacing between stations on total door-to-door journey time of commuters using BRTS is nonlinear and parabolic for all designs.
- Door-to-door travel time varies between 41.7 and 57.0 minutes for different designs and station spacing.

- Lowest travel time occurs for all BRTS design alternatives when average station spacing is approximately 750m.
- In general, passenger journey time in open systems is more sensitive to average station spacing than it is in closed systems.
- Within each category of open and closed systems, junction stations result in lower door-to-door journey time for passengers than midblock stations
- In general, staggered station provides lower journey time than island stations.

Effect of Passenger Demand Variations

- A nonlinear relationship exists between journey time and passenger demand such that for all alternatives maximum travel time saving is for a demand of between 7500 to 12500 PPHPD
- With the increase in demand for a BRT system the overall travel time of an average passenger door-to-door trip reduces by anywhere between 1 to 4.5 minutes.
- This reduction is understandable as higher bus numbers are required to cater to high demand that reduces headway, thereby reducing waiting time for passengers.

Effect of Station Distance from Stop Line at Intersection Variations

Increasing distance of stations from stop line, average passenger journey time increases in a linear relationship by 2.6 minutes. The increased walking distance for bus passengers at each end of their journey explains the journey time increase. This journey time increase does not produce a gain in vehicular speed because increased distance of boarding bay from the stop line does not affect operational speed.

Effect of Signal Cycle Length Variations

- Increasing signal cycle length leads to an increase in journey time of passengers by as much as 33% in all alternatives.
- This increase is approximately five minutes for alternatives with midblock station designs and approximately 13 minutes for alternatives with junction station design.

Increased delays caused to buses by longer signal cycles explain the increase in passenger journey time. The delay is higher for junction stations because at junction stations passengers experience increased delay in crossing the road to access the station. Since increase in signal time does not affect the midblock pedestrian signal cycle, pedestrian access time to the midblock station is not affected.

5.1.4 Access and Egress Time

Closed systems have higher access time, i.e., 33 to 42 minutes, than open systems, i.e., 18 to 25 minutes. In general, midblock stations result in higher access time than junction stations. This is because 100% of feeder based passengers encounter interchanging delays in closed system while 30% of such passengers are assumed to interchange at the BRTS corridor in an open system (S G Architects and Fazio Engineerware 2012c). Passenger demand variations do not effect access and egress time. Salient findings on ‘access cum egress time’ variations against variations in other design features are:

Effect of Average Station Spacing Variations

With increasing average station spacing, BRTS passenger access time increases for all alternatives by anywhere between 3 to 4 minutes. Increased average walking distance for commuters due to larger gaps between stations explains the increase in passenger access time.

Effect of Station Distance from Stop Line at Intersection Variations

Increasing distance of boarding bays from the stop line increases access and egress time for all BRTS design alternatives by as much as 2.3 minutes. Increased walking distance from the zebra crossing explains the increase in access and egress time.

Effect of Signal Cycle Length Variations

- Increasing signal cycle length at intersections, increases the access time by anywhere between four to nine minutes for alternates with junction stations while it remains more or less uniform for midblock stations.
- Because of higher transfers, closed system show higher sensitivity of passenger access time to increasing signal cycle length (S G Architects and Fazio Engineerware 2012c).

5.1.5 Walking Distance

In general, walking distances are shorter for junction stations than for mid-block stations and for stations without overtaking than with overtaking bus lanes. This is because of reduced distance for interchanging commuters at intersections and shorter crossing width for stations without overtaking lane than for stations with overtaking bus lanes. Variations in demand and signal cycle length have no effect on commuter walking distance. Salient findings on walking distance variations against variations in other design features are:

Effect of Average Station Spacing Variations

- Increasing average station spacing results in an increase in passenger walking distance by maximum of 300m for all alternatives.
- Walking distances are shorter for open systems i.e. 900 to 1400m, than for closed systems i.e. 1150 to 1800m.

Effect of Station Distance from Stop Line at Intersection Variations

When one increases the station to stop line spacing, walking distance increases at both ends of the journey. This is understandable as increased setback of the station from the stop line adds to overall access and egress distance.

5.2 Comparative Analysis of Two BRTS Design Alternatives in Varying Traffic

As in sixteen alternate design analyses previously mentioned, door-to-door travel time in open systems is much more sensitive to average station spacing than closed systems. This can be observed from the data presented in table 3. However, for both designs and both alternatives of average trip length, minimum trip time occurs for station spacing of approximately 750m. Comparison also shows that increasing peak bus speeds above 40km/h has little or no impact on journey time reduction for an average passenger. The advantage of increasing peak bus speed increases with increasing spacing between stations. Longer spacing between stations allows longer acceleration and deceleration times. This, in turn, allows achieving higher bus speeds between the stations. However, the time gain is small compared to overall journey time even for 1000m spacing between stations. At the optimum station spacing of 750m, average journey time at 40km/h peak bus speed, are approximately 41.2min for 6 km trip length and approximately 57.2min for 10km trip length. For the closed system, journey time is 43.2min for 6 km trip length and 55.2 minutes for 10km trip length. In all scenarios, increase in peak bus speeds beyond 60 to 70 km/h shows no advantage in time saving. At an average station spacing of 750m, the advantage in increasing the peak bus speed from 40 to 60km/h is a time saving between 1 and 2 minutes for trip lengths varying between 6 and 10km. This amounts to between 2 to 4% of the average journey time of the passenger.

The evaluation of operational speed of buses in BRTS corridor with closed operations involved varying peak bus speeds from 40 to 100km/h and spacing between stations from 500 to 1000m. As can be observed from Table 4, commercial speed increases with increasing spacing, increased peak bus speeds in the corridor does not significantly influence commercial speed. The sensitivity of commercial speeds to increase in peak bus speeds is lower for shorter average spacing between stations and higher for longer spacing and any gain is only up to approximately 60km/h beyond which increase in peak speed does not yield in much increase in commercial speed. This is understandable as higher spacing between stations provide longer opportunity for buses to accelerate and decelerate. When one increases peak speeds from 40 to 60km/h, the maximum increase in commercial speed is less than 1 km/h from approximately 21.5km/h for 500m spacing between stations. At an ideal station spacing of 750m, the increase in commercial speed is approximately 3km/h, i.e., from 23 to 26km/h. This implies that a 50% increase in peak speed only yield a 10-13% increase in commercial speed of buses on a BRT corridor in a closed system. This is even less for an open system.

The analyses show that in general commuters get higher passenger speed benefits from BRTS when an average vehicular speed along the corridor is low. As can be observed from Table 5, this gain is more for long trip lengths. For example, when average vehicular speed in non-BRTS lanes is less than 12.5km/h, commuters in BRTS register a gain of passenger speed between 4 to 5km/h in an open system and 5 to 6km/h in a closed system, for a 16km trip length. This gain is less than 2.5km/h for an average trip length of less than 6km. Passenger speed gain for BRTS commuters over general traffic drops to between 1-3km/h, when the average vehicular speed in non-BRTS lane is 22.5km/h. If the average vehicular speeds in the corridor is above 27.5km/h passenger speeds in BRTS buses is equal to or even worse than buses in mixed condition especially for open operation BRTS alternatives. This is because when traffic in mixed conditions is uncongested, and this results in high average vehicular speeds on the corridor. Buses in mixed traffic conditions move unhindered and do not gain in operational speed when segregated in exclusive lanes. However, in open bus operations without overtaking or passing lanes, buses get relatively shorter exclusive green phases. This leads to higher bus delays in segregated lanes, leading to an overall lower passenger speed in BRTS against that in mixed condition, for long trips on high-speed corridors.

Analyses of 16 different BRTS design alternatives show that operational or commercial speed of buses is better in closed systems than in open systems. However, passenger speeds in closed and open systems do not follow a similar trend. Results show that though commercial speeds are substantially higher in a closed system than in an open system, which the passenger speed is better for open systems than for closed systems for up to 9-10km trip length. This is because in a closed system 100% of passengers loose time in interchanging between feeder buses and the trunk or BRTS buses. For shorter trip lengths, time gain due to higher commercial speed in closed systems does not sufficiently offset interchanging loss time.

5.3 Comparative Analysis of Two Existing BRT Systems

The comparative evaluation of variations in two existing BRTS systems reiterates the findings of previous two stages in the study. In case of Ahmedabad, performance against all passenger indicators show improvement if modification of the current design involves one with staggered stations in open system, as against current island stations with closed bus operations. However, performance against operational indicators remains the same or drops for any of the two proposed design alternatives. In case of Delhi BRTS, performance against all passenger indicators shows a negative trend for any change in design to island stations or closed bus operations from the current staggered stations with open bus operations. However, operational indicators show improvement if one changes current station design and bus operations to island stations and closed bus operations. This is because average trip length for both Ahmedabad and Delhi is less than 10km. Though performance against operational indicators remains better with closed system for any trip length, the performance against passenger indicators is better in an open system with staggered stations for average trip length less than 10km.

6 CONCLUSIONS

This study models performance of various BRTS planning, operation and design configurations and quantifies the impact of changes in these on the overall performance against societal, passenger and operational indicators. These quantified results allow planners and designers to make sound choices to meet specific system requirements in a given context. Though closed systems generally achieve higher operational speeds than open systems, they result in a higher passenger speeds only for long trip lengths. High operational speeds do not help offset passenger transfer delays if the proportion of time spent in the vehicle is considerably shorter than accessing it. Open systems provide higher passenger speeds than closed bus operations for trip lengths less than 10km when used with stations without overtaking lanes and less than approximately 16km when stations with overtaking lanes are used.

At junctions where bus turns are permitted in open bus operations, a passing lane allows segregation of turning buses from straight buses. This lane helps in reducing delays for buses headed straight, by segregating turning buses in a separate lane. This allows straight buses to use the straight signal phase for general vehicles. This helps in significantly improving the operational and passenger speed of the system while reducing average bus and passenger delays. Operational speed of buses in open system without overtaking lanes is approximately 25% lower than what would be in a closed system, while the same is 10-15% lower if an overtaking lane is used at all turning junction stations. BRTS systems with overtaking lanes at stations help improve capacity in all types of design alternatives. Existing standards recognize the advantage of a passing or an overtaking lane at stations (Institute for Transportation and Development Policy 2011). Comparative analysis results validate this advantage. However, the results show that a passing lane is much more advantageous in open bus operations than in closed.

The results of this study show that though station location at junction or midblock has no impact on operational indicators, junction stations result in better passenger speeds than midblock station. The closer a station to the intersection, the lower is the expected passenger journey time and walking distances. However having a station too close to the stop line has a negative impact on the system capacity, and an optimum distance is 26m for all station and operation combinations. Station set further away from the junction tends to fare lower on passenger indicators without any significant advantage on operational indicators. The current standards prescribe that station locations should be minimum of 40m away from the stop line though it sets no upper limit (Hook et al. 2012). Contrary to the results of the study, this ignores the adverse impact of higher station setback from intersections on passenger indicators.

Comparative analysis results show that, in general, near side staggered stations provide better performance than island stations, for both operational and passenger indicators in both open and closed bus operations. However the existing models and standards appear universally in favor of Island stations as reducing operational, maintenance and capital costs, minimizing ROW requirements and allowing easy interchange for passengers (Institute for Transportation and Development Policy 2011). Results of this study reveal the optimum station spacing for all planning, operation and design configurations to be approximately

750m. However current standards indicate ideal average station spacing of approximately 500m (Wright and Hook 2007).

The results indicate that the BRTS corridors are more beneficial or suitable to inner city areas. The system provides no or little advantage to passengers in corridors where average speed of general motor exceeds approximately 22.5km/h. In most cities, this speed exists on peripheral areas, while inner city areas see significantly lower speeds of approximately 15km/h. The results infer that cities having an average trip length of less than 4km do not appear as a suitable candidate for a BRTS. Such short trip lengths, passenger speeds with any form of public transport will be typically less than 6km/h that is much lower than cycling speeds and comparable to walking speeds. Many current standards are silent on the effect of average trip length in the city on planning and design choices (Hook et al. 2012). From the safety perspective, peak bus speed in the system should not exceed 40km/h. In addition, increasing peak bus speed to more than 40km/h does not have a significant, direct effect, neither on passenger nor on operational speed. However, most standards do not suggest any peak speed limit for buses in the BRTS. In most cases, local laws govern the speed limit.

The results of the comparative analyses of different BRTS design alternatives provide a sound basis for decision making during planning and design stages. However it is important to note that these are based on a physical measure of indicators such as travel time, walk distance etc., and does not account for perceived time, effort, etc., which play a critical role in user behavior and satisfaction rating. In addition, the analysis does not cover comparison of capital and operational cost that play an important role in system selection. Comparing analysis results with recommendations listed in many current standards and models show that these standards and models provide general observation based guidelines and do not evaluate BRTS designs. BRTS designs are rarely uniform. In reality, individual elements do not form the sole basis of BRTS performance, which depends on complex relationships and configurations of these elements. These models treat and compare all systems on the same canvas ignoring the impact of specific context and other limitations in shaping design choices. Many current standards and models focus more on operational indicators and use the same as proxy passenger indicators. Though most of their indicators are accurate for operations, they do not directly estimate passenger related performance. It is important to include all operational, passengers and societal indicators as per their relative importance, for a complete evaluation of BRTS performance.

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