BRT STATION CAPACITY ANALYSIS: OPTIMISING BUS RAPID TRANSIT STATION DESIGN THROUGH CAPACITY ANALYSIS

R LOWE and A FRIESLAAR

HHO Consulting Engineers, 14th Floor, The Towers South,
2 Hertzog Boulevard, Cape Town, 8001; Tel: +27 (21) 425 2870;
Email: rebekah@hho.co.za and andre@hho.co.za

ABSTRACT

Bus Rapid Transit (BRT) is being prioritised in countries that want to implement fast, affordable and reliable public transport. Because this is a relatively new mode of public transport, there is limited literature dealing specifically with BRT design and design analysis. As a result, the need for a way to analyse and validate BRT related design decisions was realised.

The concept of the BRT Station Capacity Analysis Methodology was explored to assist with high-level planning and decision making on corridor design. It is a method of analysing the major components of a public transport station based on the calculated capacity of the component and the associated Level of Service criteria. The results are also used to identify areas that limit the overall functionality of a station, and areas where components are overdesigned. This process promotes sustainable design and the responsible use of resources and materials.

This paper presents the methodology for analysing station component capacities and optimising station design based on the optimal application of existing information.

1. INTRODUCTION

The concept of the BRT Station Capacity Analysis Methodology was explored to assist with the high-level planning and decision making on BRT corridors. This methodology breaks down the station into its major components, calculates the capacity for each component for a Level of Service D, and then compares the results to identify the component that limits the overall capacity of the system. This is useful because it allows designers to correlate station designs to passenger capacities, and if the expected demand (passengers per hour) is known, the appropriate station can be chosen.

The methodology for the calculation of the capacities of various elements of a BRT station is well documented. Nonetheless, there appears to be a lack of understanding as to the implications each element has on potentially limiting station capacity, or of providing unnecessary excess capacity. In order to optimise station design, it is necessary to assess the capacities of each element so appropriate design decisions can be undertaken.

2. LITERATURE REVIEW

2.1 Defining BRT

The BRT is defined as “a bus-based rapid transit system that can achieve high capacity and speed at relatively low cost by combining segregated bus lanes that are typically median aligned, off-board fare collection, level boarding, bus priority at intersections, and other quality-of-service elements (such as information technology and strong branding)” (ITDP, 2015), see Figure 1. While BRT is a relatively new mode of public transport, with the first system introduced about 50 years ago, it is steadily gaining popularity around the world.

Figure 1: MyCITI station in Cape Town (HHO, 2018)

2.2 Level of service

Level of Service (LOS) as a measure of pedestrian comfort and experience was used by the author and engineer John Fruin. Fruin (1971) describes how the flow of pedestrians (measured in pedestrians / minute / metre) along walkways and on stairways has an associated LOS based on the number of people sharing the walkway or stairway. These levels of service range from A, where pedestrian flow is completely free flowing and therefore very comfortable, to F, where pedestrian flow is severely constrained by the number of people using the walkway or stairway. This concept was expanded to include LOS descriptions for queuing pedestrians (measured in m^2 / pedestrian) in the Transit Capacity and Quality of Service Manual (TCQSM).

The pedestrian flow and space LOS values provided by TCQSM take into account the “available standing space, perceived comfort and safety, and the ability to manoeuvre from one location to another” (TCQSM, 2013). These values are used to size components of public transport stations. If the passenger demand is known and the desired LOS has been chosen, the size of various components can be calculated. Figure 2 shows the conditions that describe the six levels of service.

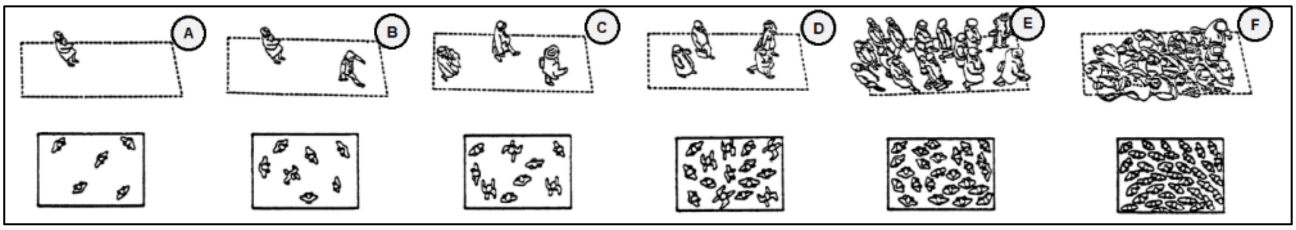

Figure 2: Illustration of Level of Service conditions for walkways (top) and queuing (bottom), (TCQSM, 2013)

TCQSM (2013) notes the importance of balancing the comfort of pedestrians with designing a practical and economically viable station. Designing for a LOS A would provide pedestrians with a high level of comfort, but would be uneconomical from a space perspective because the station would have to be very large to accommodate a reasonable number of passengers at a spacing of 1.2 m^2 / person. Designing for a higher level of service, for example, LOS D, would provide a balance between comfort and the economical use of space.

The *BRT Planning Guide, Volume 2* (Krogscheepers, C. *et al*, 2017) unpacks the limitations of using LOS as the only performance measure of a public transport system. Public transport forms only one part of the greater transportation network and should be evaluated within this context, for example, how does the placement of a station affect the general traffic at the intersection, or does the public transport system reduce the general traffic demand along that corridor. The LOS criteria are useful for describing the operation of singular elements within a system and more complex methodologies need to be considered to measure the performance of the overall transport system. The methodology presented in this paper looks at BRT stations as an isolated system, and further analysis would be required to evaluate these stations within the context of the transportation network.

2.3 Station capacity

Station capacity, or station design capacity, is the passenger demand volumes during the peak hour – in other words, the maximum number of passengers that can be facilitated by a station during the peak hour. Station capacity is a very important operational and design consideration for BRT systems because “BRT projects seek to optimize one basic parameter: minimizing door-to-door travel time” (Hook, W. *et al*, 2013). This goal is only achievable when the various elements of a BRT system work seamlessly together. Getting through the station and into a bus needs to be as easy as possible to minimise the beginning and the end portions of travelling by BRT.

The TCQSM methodology looks at sizing individual components of a station in isolation. For these calculations, the demand is known and the station design has not been confirmed yet, and so the design can change to suit the demand. For places where the demand is not known or where the design has been done, this methodology cannot be used easily to evaluate the station design and so alternative methodologies are required to assist with design decisions. A methodology focused on a constant measure to evaluate all the components is required, for example, the number of passengers per hour or capacity.

2.4 Sustainable design

Sustainable design is becoming a common term associated with engineering projects. “The basic objectives of sustainability are to reduce consumption of non-renewable resources, minimize waste, and create healthy, productive environments,” (Horn, D. and Davis, L. 2018). Sustainability does not only mean “eliminating negative environmental impact completely through skilful, sensitive design,” (McLennan, J. 2004); it calls for designers not to waste anything, including money, time and resources. In order to design in a sustainable manner, aspects of design that may lead to a waste of materials or expenditure need to be identified and changed. Station optimisation methodologies provide the means to inspect these aspects of design and to change them accordingly.

2.5 Microscopic modelling

"A macroscopic approach to station design should not be the sole method of designing a… station as these methods underestimate actual station passenger spatial requirements," (Trafficon CC, 2018). The alternative to macroscopic modelling is microscopic modelling, which uses software to model and simulate human behaviour within a station and provides realistic results. Microscopic analysis also provides a "detailed operational assessment of all public spaces," (Hermant, L. *et al*, 2010), which cannot be done by macroscopic methodologies. Microscopic analysis also produces 2D and 3D imagery of the designs, which is useful for sharing ideas with non-technical clients.

While microscopic analysis and modelling provides a lot of detail to assist with the design of stations, it often requires highly skilled modelling expertise and expensive software. However, the macroscopic modelling of station elements can be undertaken relatively quickly and at a lower cost, whilst providing the designer with accurate capacities of each station element.

3. THE METHODOLOGY

3.1 Capacity components

3.1.1 Station capacity

Stations are the overarching infrastructure that facilitates the movement of passengers through the payment system and into the buses. The station capacity is defined by the component with the lowest capacity. This component 'bottlenecks' the system and is therefore important to identify. Figure 3 gives the layout of a typical BRT station.

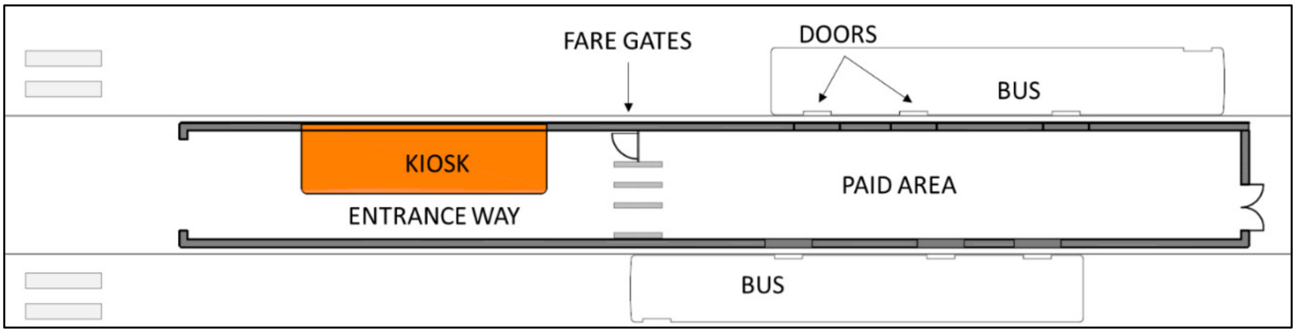

Figure 3: Typical BRT station layout

3.1.2 Entranceway capacity

The entranceway is the narrowest section of a pedestrian's path into the paid area of a station. Figure 4 shows an example of this.

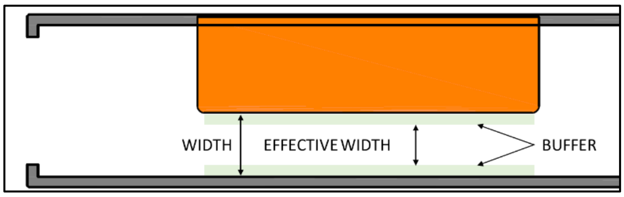

Figure 4: Entranceway

The width of the entranceway is further reduced by a buffer width adjacent to the walls or handrails on either side of the walkway. According to TCQSM (2013), the buffer width is

0.25 – 0.3 m from each obstruction (i.e. wall or handrail). Equation 1 demonstrates how the effective width is calculated.

$$w_{effective} = w_{total} - \sum w_{buffer} \quad (1)$$

The capacity of an entranceway is calculated using the equation below (adapted from TCQSM, 2013).

$$C_e = w_{eff} \times v_{LOS} \times 60 \quad (2)$$

Where,

- C_e is the entranceway capacity (passengers / hour),
- w_{eff} is the effective width of the entranceway (m),
- v_{LOS} is the LOS related passenger flow (passengers / m / minute).

3.1.3 Stairway capacity

The stairway capacity is the number of people that can cross a section of the stairway in an hour. This is calculated using Equation 2 as well, but has a lower LOS related passenger flow rate because people move more slowly on stairs, especially when going up stairs. The effective width calculation also applies to the staircase, as there is a buffer zone between the handrail and the width of the staircase used by passengers.

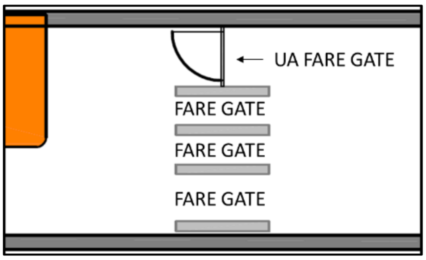

Figure 5: Fare gates

3.1.4 Fare gate capacity

Fare gates are used for off-board fare payment. Public transport users need to tap their ticket or smart card to unlock the gate and access the paid area of the station. Figure 5 illustrates the layout of fare gates, including a universally accessible gate and a wider gate for people with luggage.

The equation provided for determining the capacity of fare gates can be used for turnstiles, speed gates and universally accessible gates (adapted from TCQSM, 2013).

$$C_{fg} = N_{fg} \times C_{fg1} \times 60 \quad (3)$$

Where,

- C_{fg} is the fare gate capacity (passengers / hour),
- N_{fg} is the number of gates,
- C_{fg1} is the operational service rate of 1 fare gate.

According to L. Hermant (2013), the operational service rate of fare gates do not have an associated LOS, but rather, the upstream queue space can be evaluated with a LOS. The upstream queue space is the area required to hold passengers while they wait to enter the station through the fare gates and the LOS, in this case, is more an indication of the comfort of passengers rather than a capacity measure.

It is recommended that the queue space be evaluated once the passenger arrival rates and demand are known.

3.1.5 Paid area capacity

The paid area is the area between the fare gates and the emergency exit (see Figure 6). This, as the name suggests, is the area that a passenger can be in only once they have paid. The paid area consists of platforms and circulation space to accommodate both waiting and moving passengers.

The major factors influencing the capacity of a paid area are the platform and circulating areas, and the frequency of buses. The more buses arrive per hour, the faster the turn over of passengers in the paid area. Equation 4 was adapted from the TCQSM (2013).

$$C_{PA} = \left[\left(\frac{A_p}{A_{LOSw}} \times N_p\right) + \left(\frac{A_{ww}}{A_{LOSc}}\right)\right] \times f \quad (4)$$

Where,

- C_{PA} is paid area capacity (passengers / hour),
- A_p is the platform area (m^2),
- A_{LOSw} is the LOS waiting area required per person (m^2 / passenger),
- N_p is the number of platforms,
- A_{ww} is the circulating and walkway area (m^2),
- A_{LOSc} is the LOS circulating area required per person (m^2 / passenger),
- f is frequency (bus / hour).

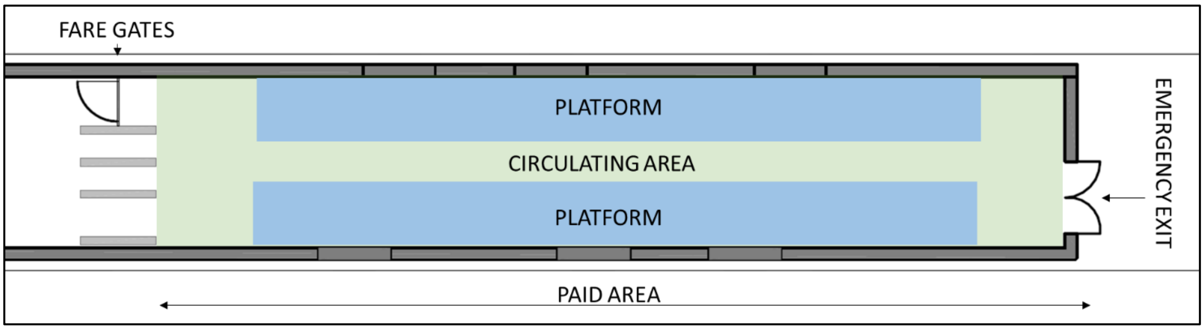

Figure 6: Paid area

3.1.6 Doorway capacity

The doorway capacity is the total number of people that can pass through the station and bus doors into or out of the bus in an hour. Equation 5 is used to calculate this capacity (adapted from TCQSM, 2013).

$$C_d = w \times N_d \times v_{LOS} \times f \times t_d \quad (5)$$

Where,

- C_d is the door capacity (passengers / hour),
- w is the width of the doors (m),
- N_d is the number of doors,
- v_{LOS} is the maximum passenger flow (pedestrians / m / minute),
- f is frequency (bus / hour),
- t_d is the dwell time (minutes).

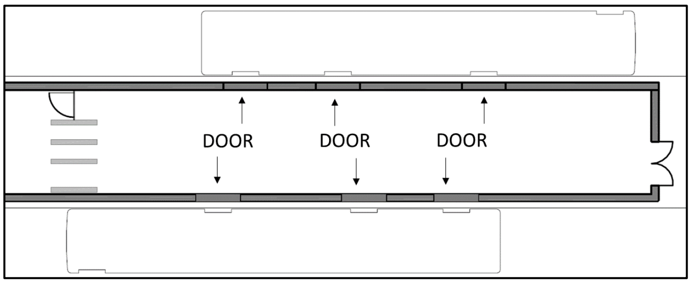

Figure 7: Station to bus doorways

Door capacity is heavily reliant on the dwell time and frequency of buses. While a long dwell time ensures a high number of people can board and alight, the efficiency of the BRT system requires shorter dwell times, and so a balance is required to accommodate both needs.

3.1.7 Bus capacity

The bus capacity is the number of people that are moved from a particular station by bus in an hour. This capacity is calculated using Equation 7 below (adapted from TCQSM, 2013).

$$C_b = V_b \times N_p \times f \qquad (6)$$

Where,

- C_b is bus capacity in (passengers / hour)
- V_b is the LOS related capacity of each bus (passengers / bus)
- N_p is the number of platforms
- f is bus frequency (bus / hour)

3.2 Data collection

The LOS values are constant parameters provided by TCQSM (2013). The desired LOS is D because it balances the need for passenger comfort with system efficiency. Table 1 summarises the relevant LOS values.

Table 1: LOS values

			LOS D	UNIT	REFERENCE
1.	Walkway Flow [1]	v_{LOS}	66	pax / m / min	Exhibit 10-28
2.	Doorway Flow [1]	v_{LOS}	66	pax / m / min	Exhibit 10-25
3.	Pedestrian Flow (Staircase) [1]	v_{LOSs}	43	pax / m / min	Exhibit 10-28
4.	Pedestrian Queuing Space [1]	A_{LOSw}	0.3	m^2 / pax	Exhibit 10-32
5.	Pedestrians Flow Area [1]	A_{LOSc}	0.9	m^2 / pax	Exhibit 10-28
6.	Bus Capacity (9 m) [1]	$V_{a/b}$	40	pax / bus	Exhibit 5-16
7.	Bus Capacity (12 m) [1]	V_b	70	pax / bus	Exhibit 5-16
8.	Bus Capacity (18 m) [1]	V_b	100	pax / bus	Exhibit 5-16

([1] TCQSM, 2013)

The other values that make up the equations are linked to specific design and planning aspects of the station. These variables can be changed to optimise the design and operation of the system. Table 2 lists the variables and gives values for a hypothetical station called Station 1, shown in Figure 8.

Table 2: Station data for Station 1

			VALUE	UNIT
1.	Area of one platform	A_p	19	m^2
2.	Area of walkway	A_{ww}	23	m^2
3.	Area of entrance queue space	A_{qu}	9	m^2
4.	Capacity of one fare gate	C_{fg1}	25	pax / min / gate
5.	Dwell Time	t_d	30	seconds
6.	Frequency (maximum)	f	30	buses / h
7.	Number of doors	N_d	6	-
8.	Number of fare gates	N_{fg}	3	-
9.	Number of platforms	N_p	2	-
10.	Width of doorway	w	1.1	m
11.	Effective width of entrance / stairway	w_{eff}	1.5 - 0.5 = 1.0	m
12.	Bus typology		18 m bus	

At this stage, it is assumed that the buses are unoccupied when they arrive and they empty the platform.

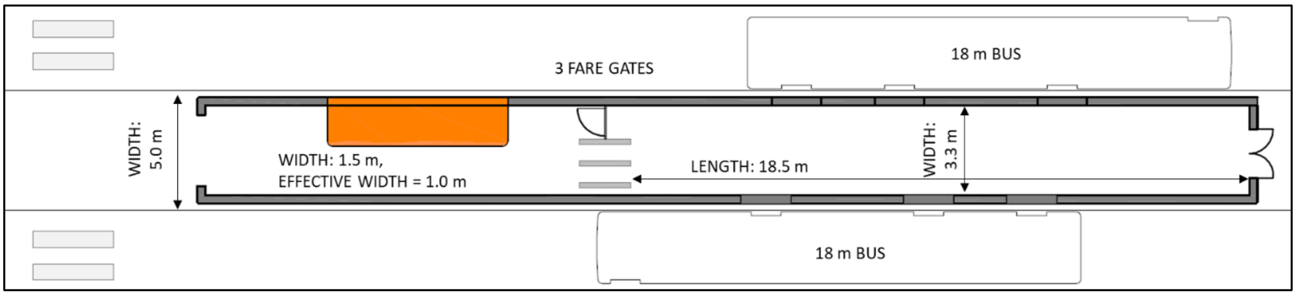

Figure 8: Station 1 layout and dimensions

3.3 Calculations

Once all the variables and LOS values have been collected, the capacities for the relevant components can be calculated. In the example of Station 1 depicted in Figure 8, only the entrance, fare gate, paid area, door and bus capacities are relevant.

Figure 8 shows worked examples for Station 1 using the data in Tables 1 and 2.

The limiting capacity is the component with the lowest capacity value, which also dictates the overall station capacity. From Figure 8, it can be seen that the entrance is the limiting component for Station 1.

Entrance Capacity (2)

$$C_e = w_{eff} \times v_{LOS} \times 60$$
$$C_e = 1.0 \times 66 \times 60$$
$$C_e = 3960\ passengers/hour$$

Fare Gate Capacity (3)

$$C_{fg} = N_{fg} \times C_{fg1} \times 60$$
$$C_{fg} = 3 \times 25 \times 60$$
$$C_{fg} = 4500\ passengers/hour$$

Paid Area Capacity (4)

$$C_{PA} = \left[\left(\frac{A_P}{A_{LOSw}} \times N_p\right) + \left(\frac{A_{ww}}{A_{LOSc}}\right)\right] \times f$$
$$C_{PA} = \left[\left(\frac{19}{0.3} \times 2\right) + \left(\frac{23}{0.9}\right)\right] \times 30$$
$$C_{PA} = 4650\ passengers/hour$$

Doorway Capacity (5)

$$C_d = w \times N_d \times v_{LOS} \times f \times t_d$$
$$C_d = 1.1 \times 6 \times 66 \times 30 \times 0.5$$
$$C_d = 6534\ passengers/hour$$

Bus Capacity (6)

$$C_b = V_b \times N_p \times f$$
$$C_b = 100 \times 2 \times 30$$
$$C_b = 6000\ passengers/hour$$

Figure 8: Worked examples

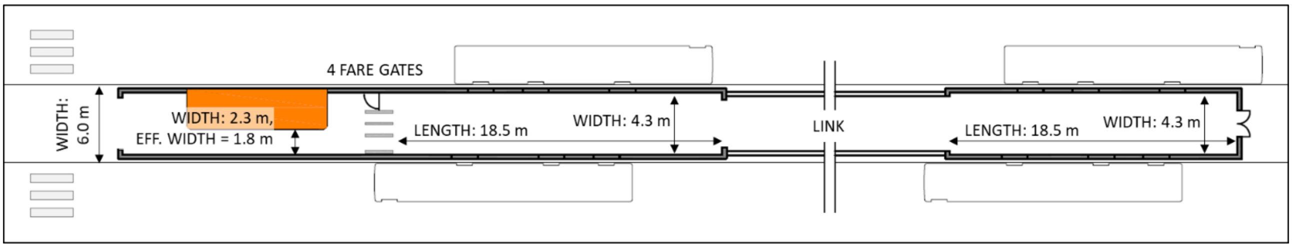

Figure 9: Station 2 layout and dimensions

Figure 9 is an example of a double pod station. When the same calculations are done for this station typology, the limiting component changes. Table 3 summarises the results of both stations and highlights the limiting component of each.

Table 3: Summary of worked example results

	STATION 1	STATION 2
Entrance Capacity	3 960	7 128
Fare Gate Capacity	4 500	6 000
Paid Area Capacity	4 650	12 000
Doorway Capacity	6 534	13 068
Bus Capacity	6 000	12 000
Limiting Component:	**Entrance**	**Fare Gate**

4. SUMMARY OF FINDINGS AND DESIGN CONSIDERATIONS

Based on the results of the capacity analysis of a single and double pod station, the following design considerations are highlighted, and should be used to inform the appropriate design of median BRT stations:

4.1 Entrance walkway capacity

Being in the median of roadways, station width is often a constraint, and station widths typically vary from 3.5 metres to 6 metres. Furthermore, the kiosk is often placed between the pedestrian crossing and the fare gates, thereby narrowing the entrance walkway.

- The walkway should be a minimum of 1.5 metres between handrail and kiosk, which will provide a two-way capacity of approximately 4 000 passengers per hour. Every 0.5 metres of width added to the walkway will provide an additional 2 000 pass/hr throughput.
- Should the capacity of the station exceed 4 000 passengers per hour, the walkway will need to be widened, by either widening the station, narrowing the kiosk, or relocating the kiosk out of the walkway. In CBD environments, consideration can be given to having entrances on both ends of the station, which could effectively double the walkway capacity.
- The kiosk sales window should not face onto the walkway, as this will result in queueing in the walkway, significantly reducing its capacity for through traffic.

4.2 Gate area capacity

Similarly, the station width will physically limit the number of gates that can be installed, and the capacity of the fare gate area is related to the number of gates provided.

- Typically a fare gate can accommodate approximately 1 500 passengers per hour
- This translates to a gate area capacity of:
- Effective station width up to 3.3 metres (2 gates) – 3 000 pass/hr
- Effective station width 3.3 to 4.1 metres (3 gates) – 4 500 pass/hr
- Effective station width 4.1 to 4.9 metres (4 gates) – 6 000 pass/hr
- In CBD environments, further gate capacity can be achieved by providing entrances and gate areas at both ends of the station.
- Further gate area capacity can be achieved in wider stations (>4 metres) by staggering gates.

4.3 Paid area capacity

- Paid areas for single pod stations are typically a minimum of the length of the design vehicle, for example, 18 metres for 18 m buses
- Paid areas for multiple pod stations are characterised by multiple pods and one or more links, which are typically 1.7 times the length of the design vehicle.
- Paid area capacity is heavily dependent on bus frequency and the availability of seats in each bus – in essence, you can only accommodate the number of people in the station that the buses can physically take away. This implies that a poor operational plan will result in a build-up of passengers in a station, potentially exceeding the paid area capacity.
- A single station pod for a typical 5 m wide station can accommodate approximately 150 passengers at any one time, but increases to approximately 4 500 passengers per hour based on a 2 minute bus frequency and a 100% availability of seats on each bus. This value drops dramatically to 1000 pass/hr, with the same bus frequency, but only 25% of seats available on each bus.
- In general, multiple pod stations with links have very high paid area capacities, and hence are not a limiting factor in station design, provided the operational plan services the station passenger demand.

4.4 Doorway capacity

BRT stations and buses are typically equipped with multiple doors for rapid boarding and alighting.

- Doorway capacity is heavily dependent on the number of doors, bus frequency and the bus dwell time – in essence, approximately 210 passengers per minute can be accommodated through 3 doors (1.1 m width) of an 18 m bus (or 70 passengers per minute per door).
- In essence, based on the above flow rates, a full 18 metre vehicle could be emptied and filled through the three doors in less than 2 minutes.
- Practical minimum dwell times are approximately 15 seconds, in which time 55 passengers can board and alight through 3 doors, which doubles to 110 passengers if the dwell time is extended to 30 seconds.
- The doorways are therefore not a limiting factor in station design, provided that bus frequencies and dwell times are matched with boarding and alighting demands.

4.5 Bus capacity

This defines the capacity of the buses to deliver or remove passengers from a station.
Bus capacity is highly dependent on the number of platforms and bus frequency.

- A further consideration is how full the buses are, which will limit their capacity.
- A typical platform has a capacity of 3 000 passengers per hour based on a 2 minute headway of empty 18m buses.
- Once again, the operational plan will need to match platform demand by scheduling enough bus capacity. If demand exceeds the bus capacity, the paid area capacity may be exceeded and passengers will be forced to queue outside of the station.

5. RECOMMENDATIONS AND CONCLUSION

This paper has sought to investigate the macroscopic capacity calculations of various key station elements in order to provide some design considerations that may influence appropriate and balanced station element design.

In order to ensure that stations are being appropriately designed in South Africa, it is recommended that:

- The TCQSM design parameters be either ratified for South African conditions, or local parameters (and LOS thresholds) established.
- All stations are designed under close collaboration between the infrastructure, systems planning and operational planners.
- Design considerations highlighted in the findings of this paper, be taken into account.

In conclusion, this methodology provides a tool specifically adapted for BRT station design evaluation, made accessible to all people working within the designing, planning and implementation of BRT and focused on a single element - capacity.

6. REFERENCES

Bulman, A, Greenwood, G & Kingma, R, 2014. *MyCiTi Bus Rapid Transit, It is not just about the Bus.* Available at: https://repository.up.ac.za/bitstream/handle/2263/45541/Bulman_Myciti_2014.pdf;sequence=1 [2018, July 24].

Frieslaar, A *et al*., 2017. *The BRT Planning Guide*. 4th Edition. Volume 6: Infrastructure. Available at: https://brtguide.itdp.org/branch/master/guide/volume/infrastructure [2018, July 24].

Fruin, J, 1970. *Designing for Pedestrians: A Level-of-Service Concept.* New York: Polytechnic University of Brooklyn.

Hermant, L, 2013. *A Methodology for the Determination of Access Gate/Turnstile Upstream Spatial Requirements and Level of Service.* Rio de Janeiro: World Conference on Transport Research.

HHO, 2018. *MyCITI Station in Cape Town* [Image].

Hook, W *et al*., 2017. *The BRT Planning Guide*. 4th Edition. Volume 2: Operations. Available: https://brtguide.itdp.org/branch/master/guide/volume/operations [2018, July 24].

Horn, D and Davis, L, 2018. *Sustainable Design*. Available at: https://www.gsa.gov/real-estate/design-construction/design-excellence/sustainability/sustainable-design [2018, December 13].

Institute for Transportation & Development Policy. 2015. *The BRT Standard*. Available at: https://www.itdp.org/2016/06/21/the-brt-standard/ [2018, December 13].

Krogscheepers, C *et al*, 2017. *The BRT Planning Guide*. 4th Edition. Volume 5:Technology. Available at: https://brtguide.itdp.org/branch/master/guide/volume/technology [2018, July 24].

McLennan, J, 2004. *The Philosophy of Sustainable Design: The Future of Architecture.* Kansas City: Ecotone.

Trafficon cc, 2018. *MyCiTi Racecourse Station Modelling, Technical Note 02.* Cape Town: Transport and Urban Development Authority.

Transport Research Board Committee. 2000. *Highway Capacity Manual*. 4th Edition. United States: Transport Research Board.

Transport Research Board Committee. 2013. *Transit Capacity and Quality of Service Manual.* 3rd Edition. United States: Transport Research Board.