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Critical Station Practical Capacity on a Bus Rapid Transit Line with Non-stopping Buses

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ABSTRACT

Bus Rapid Transit (BRT) can offer transit mobility to meet growing travel demands by providing high capacity and quality of service cost-effectively. It is adaptable to a wide range of operating conditions and technological advancements. Stations are elements that typically control BRT line capacity, so it is essential to understand operation of any potentially critical station in order to understand and manage the facility. The Transit Capacity and Quality of Service Manual (TCQSM) *(1)* provides the standard methodology for capacity estimation. However, that model does not account for important operational aspects including the stochastic nature of many parameters beyond dwell time, along with non-stopping buses' capacity, degrees of saturation of the stopping and non-stopping bus streams, and upstream average waiting time and queue length of stopping buses. We adapt theory developed by Hisham et al. *(2)* for an on-street bus stop to reflect operational conditions of a BRT station and to account for these aspects. This new reliability-based capacity model tailored to BRT facilities provides superior insight into station bus capacity and quality of service than the TCQSM model.

Keywords: Bus Rapid Transit, BRT, Station, Transit Capacity, Degree of Saturation, Queue Length

INTRODUCTION

Bus Rapid Transit (BRT) systems use dedicated lanes or guideways and oftentimes advanced vehicles and technology to improve capacity, reliability, performance and quality and service over conventional on-street bus (OSB) systems. One of the many advantages of BRT systems is their ability to be developed and operated economically to suit a wide range of environments. 'Rede Integrada de Transporte' commenced service in Curitiba, Brazil in 1974 and has since inspired many high-standard BRT systems in over 44 countries worldwide *(3)*. Because BRT systems contain features similar to a light rail or subway system, they are often considered more reliable, convenient and faster than regular bus services *(4)*.

The success of a BRT system is highly dependent upon network topology, station typology, location, spacing and design. Stations often provide level boarding using either low-floor buses at curb height, or higher boarding platforms. Because buses operate at higher frequencies than OSB, stations have a vital role in maintaining efficient operation through sufficient capacity and quality of service (QOS).

We define a BRT line as a corridor containing multiple segments, which carries one or more bus routes. We define a guideway as the actual roadway that carries the buses. While a BRT station may have various configurations, our study is limited to a directionally separated station where buses cannot overtake across the oncoming side of the guideway. It includes a linear platform in each direction to serve passengers. Each platform contains multiple, off-line linear loading areas (**Figure 1**). In each direction the guideway contains an adjacent passing lane for stopping buses to negotiate around each other when accessing or egressing loading areas, and for non-stopping buses to pass through the station.

When the adjacent lane at an OSB stop carries a high volume of general traffic, interaction between buses and non-stopping vehicles will affect vehicle capacity and QOS of the bus facility (*2*). Likewise, at a BRT station with non-stopping buses, it is essential to understand the operation of any potentially critical station in order to manage the facility.

Transit facility – or line – capacity is defined by TCQSM as the 'maximum number of transit vehicles that can pass a given location during a given time period' (*1*). The given location is usually the critical station, which is the busiest station that causes the greatest restriction to line capacity. The time period is usually a peak hour in the peak travel direction. Critical station capacity is the product of capacity of each of its loading areas and the number of effective loading areas. A traffic blockage factor due to general traffic in the lane used by the buses is applicable to a stop near a signalized intersection.

The analytical model of the TCQSM methodology includes an operating margin to accommodate irregularities in buses' dwell times. Added to dwell time, this yields the maximum amount of time that a bus can dwell on a loading area without creating a 'bus stop failure'. TCQSM defines failure as a situation that arises when a bus arrives to use a loading area only to find another bus is still occupying it (*1*). This implies that all buses arrive at the loading area on schedule (at even headways) and that a failure is an isolated event that is remedied as soon as the bus causing the failure departs the loading area.

Bunker (*6*) argued that the TCQSM model is reasonable for relatively evenly spaced arrivals between successive buses, which may be the case for a bus line with relatively widely spaced headways. However, for high volume bus stops – such as BRT stations – the headways between arriving buses will be stochastic due to bunching, asynchronous scheduling between routes, and platooning caused by any nearby upstream signalized intersection. Processing times on the loading area will also vary, rather than being a fixed value equal to the inverse of the inverse of effective design capacity, which is a key assumption of the TCQSM model. Through simulation that incorporated this stochasticity, Bunker (*6*) developed a model to estimate upstream average waiting time for stop types including BRT stations. This time reflects horizontal queue accumulation upstream of the station and its impact on facility performance, which the failure rate approach does not.

Hisham et al. (*2*) accounted for upstream waiting time in development of a Bus Stop Maximum Working Capacity with Adjacent Lane Traffic' (BMWCA) model to estimate on-street, mid-block, off-line OSB capacity.The BMWCA model accounts for stochastic events near an on-street, mid-block, off-line bus stop, which is also relevant to a BRT station, such as variability in bus arrivals pattern and interference between buses caused by it. The model allocates a parameter defined as 'processing margin' for the whole stop rather than by consideration at the loading area level. It also quantifies degree of saturation of adjacent lane traffic and maximum working degree of saturation and capacity of the bus stop as a function of specified upstream average waiting time, adjacent lane flow rate and input parameters used in the TCQSM model (*2*). However, this model was developed considering a scenario of an on-street, mid-block, off-line bus stop.

This study aims to improve and extend the BMWCA model to reflect BRT station operation, to ensure that sufficient capacity is available for the non-stopping buses in the adjacent passing lane, and that upstream waiting times and queue lengths of stopping buses are maintained to acceptable levels. To achieve this aim, a Literature Review on bus facility capacity is provided in the next section. The Method section reviews the TCQSM model of BRT line bus capacity estimation, develops an improved model to estimate BRT line bus capacity, and details an analytical testbed to compare the TCQSM and improved models. The Results section details, for this testbed, practical capacity and degree of saturation calculations, details and evaluates the relationship between stopping buses' maximum working capacity and non-stopping buses' flow rate, and details and evaluates the relationship between stopping buses' average upstream queue length and non-stopping buses' flow rate. This is followed by Conclusions, which include recommendations for further research.

LITERATURE REVIEW

Bus transit capacity depends on number vehicles, operation of vehicles, passenger and traffic volumes and operating policies of the transit agency (*7*). Two types of capacity measures are considered to measure BRT line (facility) capacity; facility bus capacity and facility person capacity (*8*). This study focuses on bus capacity, which is estimated at the critical station considering loading area bus capacity, station bus capacity, and line bus capacity.

Highway Capacity Manual (HCM) (*9*) introduced an empirical model to estimate BRT line bus capacity. Levinson and St. Jacques (*7*) modified this equation using field studies and simulations, incorporating failure rate to estimate maximum achievable capacity. They used a coefficient of variation of dwell times of 60% and concluded that maximum achievable capacity corresponded to a 25% failure rate. Wang et al. (*10*) estimated failure rate through diffusion approximation with a similar theoretical concept. Many studies determined facility bus capacity using a specific value of failure rate. However, for a bus stop with a single loading area Gu et al. (*11*) defined failure rate (FR) differently from any other study. For uniform bus arrivals, they assumed that bus service time follows an Erlang-k distribution. They set the ratio of bus inflow (λ), to loading area service time (μ) equal to $FR^{\frac{C_v}{1.58+0.63C_v}}$; where C_v is the coefficient of variation of service time.

Some studies related facility bus capacity to bus stop location (*12*, *13*). Others considered stochasticity and randomness in capacity estimation. Ortiz and Bocarejo (*14*) estimated capacity of the Transmillenio Bogota using a VISSIM microscopic simulation model. They quantified the difference in capacities when randomness of bus system operations is included. Siddique and Khan (*15*) used a NETSIM microscopic simulation model to evaluate BRT facility capacity in Ottawa, Canada. With three scenarios presented, they compared estimated capacity with the TCQSM model to highlight the importance of incorporating stochasticity.

Many studies examined operational measures to increase facility bus capacity. Fernández (*16*) used microscopic simulation to evaluate the increased performance of a divided bus stop over that of a regular, multi-berth bus stop. Gardner et al. (*17*) and Germani and Szasz (*18*) found that dispatching buses in an ordered manner could increase capacity. St. Jacques and Levinson (*19*) proposed reconfiguration of stop geometry.

Fernández and Planzer (*20*) identified degree of saturation (volume to capacity ratio) of a bus station to be an important capacity estimation measure. Hidalgo et al. (*21*) incorporated degree of saturation of a sub-stop. They used a degree of saturation of 0.6 considering three sub-stops with a queueing capacity of two buses at each. They found that practical capacity increased by increasing the number of sub-stops, platforms and queuing capacity at stations, improving operational reliability and enhancing control strategies to allow higher saturation levels.

The TCQSM model (*1*) relates failure rate to desired level of operation where dwell time is assumed to be distributed normally. TCQSM states that "design capacity is effectively maximized at a failure rate of 25% and the capacity achieved with a 25% design failure rate is termed *maximum capacity*. Mathematically, throughput would be the highest if a constant queue of buses existed to move into a bus stop (a 100% failure rate)…". We argue that latter part of this statement should be changed to "…throughput would be the highest if a constant supply of buses existed to move into a bus stop (a 50% failure rate)…" because a value of the standard normal variable of 0.000 corresponds to a right tail of the standard normal distribution equal to 0.5, such that the operating margin is equal to 0s ($t_{om} = c_v Z t_d$; where c_v = Coefficient of variation of dwell time, Z = Standard normal variable corresponding to failure rate being the right tail of the standard normal distribution, t_d = Average dwell time (s)). Given the assumption of even arrival headways, under this condition a following bus would always be ready to replace a preceding bus. Whereas a 100% failure rate mathematically could be approached but not be reached back toward the left tail of the standard normal distribution, which would result in an extremely large, negative operating margin.

This study addresses two major gaps. First, the TCQSM model estimates station bus capacity using failure rate. Even though many studies have used the model including design failure rate, the definition of failure and its actual implications have not been sufficiently studied. Degree of saturation of a bus stop has been identified as a crucial parameter that ensures a desired level of service, however it has not been incorporated into capacity estimation. Second, the TCQSM model implies a reduction in bus stop capacity with an increase in non-stopping buses in the adjacent passing lane flow rate due to the bus re-entry gap acceptance process. However, it does not account for time required by non-stopping buses to pass without exceeding practical saturation flow rate.

METHOD

Review of TCQSM Model of BRT Line Bus Capacity Estimation

TCQSM (*1*) defines a loading area as a section of the stop that is designated for a single bus to stop and dwell to serve passengers. This study is concerned with a BRT station whereby other non-stopping buses can pass the loading areas while buses are dwelling. Our testbed of a typical station on the BRT system in Brisbane, Australia includes a linear platform with three loading areas in series on an off-line lane and no signalized intersection within influence of the station. Therefore, green time ratio (g/C) and traffic blockage adjustment factor (f_{tb}) are not relevant.

Stopping bus capacity is equal to the product of the number of buses that can be served by a single loading area and the number of effective loading areas according to **Equation 1**:

$$B_s = \frac{3600 N_{el}}{(t_c + t_d + t_{om})} \qquad (1)$$

Where B_s = station stopping bus capacity (bus/h), t_c = Clearance time (s) equal to sum of start-up time (t_{su}) plus re-entry delay per bus (t_{re}), N_{el} = Number of effective loading areas, and t_d and t_{om} were defined above.

Start-up time is the time taken by a bus to start up and travel its own length and next bus to pull in. It is a fixed value that corresponds to the mechanical and dimensional properties of the buses.

Re-entry delay is the time consumed as the stopping bus driver seeks an acceptable gap to re-enter the passing lane, according to **Equation 2**:

$$t_{re} = \frac{3600}{c_{re}} + 900\left[\frac{N_{la}}{c_{re}} - 1 + \sqrt{\left(\frac{N_{la}}{c_{re}} - 1\right)^2 + \left(\frac{3600}{c_{re}}\right)\left(\frac{N_{la}}{c_{re}}\right)\left(\frac{1}{450}\right)}\right] - 3.3 \quad (2)$$

Where t_{re} = Re-entry delay (s), N_{la} = Number of actual loading areas, and c_{re} = Capacity of re-entry movement (bus/h) according to **Equation 3**:

$$c_{re} = b_{ns}\frac{e^{-b_{ns}t_{ch}/3600}}{1 - e^{-b_{ns}t_f/3600}} \quad (3)$$

Where b_{ns} = Demand flow rate of non-stopping buses (bus/h), t_{ch} = Re-entry critical headway (s) = 7.0s, and t_f = Follow-up headway of re-entry movement (s) = 3.3s (*1*).

The number of effective loading areas reflects the reduction in capacity due to interference between buses (*22*, *23*). A bus stop having multiple loading areas has a greater underutilization of loading areas due to buses interfering with each other's ability to access or egress a loading area.

Development of Improved Model to Estimate BRT Line Bus Capacity

This development extends the 'Bus Stop Maximum Working Capacity with Adjacent Lane Traffic' (BMWCA) model developed by Hisham et al. (*24*) for on-street, mid-block, off-line bus stops, to BRT operations.

Loading Area Bus Processing Time

Our BRT Facility Practical Capacity (BRT-PC) model considers loading area operation as being the fundamental building block of station operation. Loading area average total processing time per stopping bus, t_{la} may be considered as the sum of fundamental components according to **Equation 4**:

$$t_{la} = \left(t_{su} + t_{bbi} + t_d + t_{re} + t_{pm}\right) \quad (4)$$

Where t_{su}, t_d and t_{re} were defined above, t_{bbi} = Time increment (s) due to interference between stopping buses, and t_{pm} = Margin on loading area average total processing time per stopping bus (s). It is important to note that, as with the TCQSM model, passenger demand effects are directly incorporated into the BRT-PC model through the dwell time, which is taken to be the average. However, rather than an operating margin on dwell time alone, the BRT-PC model incorporates the margin on dwell time as part of the loading area processing margin, which also considers stochasticity of other parameters.

The loading area average total processing time per stopping bus net of processing margin (s) is calculated according to **Equation 5**:

$$t_{la,net} = \left(t_{su} + t_{bbi} + t_d + t_{re}\right) \quad (5)$$

Hisham et al. (*24*) stated that this model implies a maximum feasible degree of saturation of the bus stop (station) itself as 1.0, should a value of zero be assigned for the margin on loading area average total processing time per stopping bus. The margin on loading area average total processing time per stopping bus (s) is calculated according to **Equation 6**:

$$t_{pm} = t_{la}(1 - X_{la}) \tag{6}$$

Equation 6 ensures that, on average, the loading area remains idle for a portion of total loading area processing time per stopping bus, which is equal to one minus a designated loading area degree of saturation, X_{la}.

By definition $t_{la,net} = t_{la}X_{la}$, so processing margin can therefore be restated according to **Equation 7**:

$$t_{pm} = \frac{t_{la,net}(1 - X_{la})}{X_{la}} \tag{7}$$

The time used by each stopping bus to negotiate around other stopped buses in both the platform lane and the passing lane at the station area is accounted for in the term, t_{bbi}.

The time available for non-stopping buses to pass during average total loading area processing time per stopping bus (s) is equal to the sum of the time components of average total loading area processing time per stopping bus, during which the bus does not obstruct the passing lane, and is calculated according to **Equation 8**:

$$t_{ns} = t_d + t_{re} + t_{pm} \tag{8}$$

An important difference between the BRT-PC and TCQSM models is that we acknowledge that when no stopping buses are present, non-stopping bus traffic has a theoretical capacity (bus/h), which we modify from (*24*) according to **Equation 9**:

$$B_{ns} = s_{ns}\left(\frac{t_{ns}}{t_{la}}\right) \tag{9}$$

Where s_{ns} is the saturation flow rate of non-stopping buses (bus/h). The degree of saturation of non-stopping bus traffic is calculated according to **Equation 10**:

$$X_{ns} = \left(\frac{b_{ns}}{B_{ns}}\right) \tag{10}$$

Where b_{ns} is the actual flow rate of non-stopping buses (bus/h).

Equation 5 requires stopping bus re-entry delay to be quantified. The BRT-PC model incorporates the gap acceptance approach according to Equations 2 and 3. However, we acknowledge that non-stopping buses are obstructed during start-up time and bus-bus interference time. Therefore, the re-entering bus driver will see a compressed stream of non-stopping buses during other times. For purposes of estimating re-entry delay due to gap acceptance, from (*24*) we adjust non-stopping bus flow rate according to **Equation 11**:

$$b_{ns}^{*} = b_{ns}\left(\frac{t_{la}}{t_{ns}}\right) \tag{11}$$

Using Equations 9 and 10, adjusted non-stopping bus traffic flow rate is calculated according to **Equation 12**:

$$b_{ns}^{*} = X_{ns} s_{ns} \tag{12}$$

We substitute b_{ns}^{*} for b_{ns} in Equation 3 to estimate re-entry delay, t_{re}. In estimating re-entry capacity, we must consider appropriate values of follow-up headway and critical gap. The value of follow-up headway of a bus re-entering behind a leading vehicle in an adjacent lane is specified by TCQSM as 3.3s (*1*). The default case is an OSB stop, where many leading vehicles are passenger cars. In our case all lead vehicles are buses that are longer than passenger cars, so lead headway might ordinarily be higher. However, at a BRT station the relative speeds between re-entering and non-stopping buses are generally lower than on-street conditions, lane geometry of the platform lane and passing lane are adequate, and drivers are trained to be co-operative. In the absence of field data, we consider that a follow-up headway of 3.3s is also reasonable at a BRT station.

Critical gap lies between the largest gap rejected by a driver and their accept gap. Maximum likelihood is the most commonly used method of estimating population critical gap (*25*). However, with few rejected gaps able to be observed at a BRT station, it is very difficult to estimate population critical gap of re-entering bus drivers from field data. As with follow-up headway, we consider that it is reasonable to adopt the TCQSM value of critical gap equal to 7.0s at a BRT station.

From (*24*) interference between stopping buses at a station may be reflected by the bus-bus interference factor according to **Equation 13**:

$$f_{bbi} = \frac{N_{el}}{N_{la}} \tag{13}$$

Where N_{el} is the number of effective loading areas according to TCQSM (*1*) values and N_{la} is the number of actual loading areas.

The additional time component towards average total processing time per stopping bus due to bus-bus interference (s/bus) can be estimated as a margin upon the sum of the time components of loading area average processing time per stopping bus, excluding processing margin, according to **Equation 14**:

$$t_{bbi} = (t_{su} + t_d + t_{re})\left(\frac{1}{f_{bbi}} - 1\right) \tag{14}$$

The system of Equations 5 through 14 allows us to determine loading area average total processing time per stopping bus, and the time available for non-stopping buses to pass during this time, provided that all inputs are specified. Assuming all loading areas on the platform are utilized equally, each of these time components – and their total – apply to each of the loading areas.

Start-up time and average dwell time are typically analysis inputs. However, according to Equation 12, we must know non-stopping buses' degree of saturation to determine stopping bus re-entry delay. The additional time component towards average total processing time per stopping bus due to bus-bus interference (s/bus) can then be determined directly using Equation 14. Further, according to Equation 7, we must know loading area degree of saturation to calculate processing margin. Therefore, these two degrees of saturation must be input in order to solve the whole system of equations. These inputs are now addressed.

Relationship between Stopping Buses' Practical Capacity and Non-stopping Buses' Flow Rate

To further develop the BRT-PC model it is useful to establish this relationship. We define practical degree of saturation as the greatest value that maintains acceptable, uncongested operation.

First, we determine non-stopping buses' practical capacity which occurs at a frontier where both: non-stopping buses reach their practical degree of saturation, $X_{ns,fr}$ and the station's loading areas – assuming equal utilization – are operating at practical degree of saturation, $X_{la,fr}$. Non-stopping buses' practical capacity may be proven according to Equation 15:

$$B_{ns,fr} = B^*_{ns,fr}\left(1 - X_{la,fr}\left(\frac{\left(t_{su} + t_{bbi,fr}\right)}{t_{la,net,fr}}\right)\right) \tag{15}$$

Where non-stopping buses' practical maximum flow rate, $B^*_{ns,fr} = X_{ns,fr}s_{ns}$, and the factor in highest level parenthesis is equal to the probability that the loading area is not: jointly occupied and causing blockage on the passing lane at practical saturation. In order to calculate $t_{bbi,fr}$ and $t_{la,net,fr}$, we must first calculate $c_{re,fr}$ and $t_{re,fr}$ by substituting adjusted flow rate with $B^*_{ns,fr}$. Then $X_{la,fr}$ is calculated using Equation 22 for the value of $t_{la,net,fr}$. $X_{ns,fr}$ needs to be specified directly, which we discuss below.

Second, we determine non-stopping buses' degree of saturation for any given non-stopping buses' flow rate, $b_{ns} \in \left(0 \ldots B_{ns,fr}\right)$ according to **Equation 16**:

$$X_{ns} = \left(\frac{b_{ns}}{s_{ns}}\right)\left(1 - X_{la,p}\left(\frac{\left(t_{su} + t_{bbi,p}\right)}{t_{la,net,p}}\right)\right)^{-1} \tag{16}$$

This formula is the quotient of the non-stopping buses' flow ratio and the probability that the loading area is not: jointly occupied and causing blockage on the passing lane at practical saturation.

Non-stopping buses' degree of saturation, X_{ns}, needs to be estimated as a function of $t_{bbi,p}$ and $t_{la,net,p}$, which are in turn a function of $c_{re,p}$ and $t_{re,p}$. To calculate these components, we use adjusted non-stopping buses' flow rate, b^*_{ns}, which is recursively a function of X_{ns}. Therefore, we need to meet the objective function of **Equation 17** to determine non-stopping buses' degree of saturation for the given non-stopping buses' flow rate:

$$X_{ns} = \underset{X_{ns,i+1}}{\operatorname{argmin}}\left(\left|X_{ns,i+1} - X_{ns,i}\right|\right) \tag{17}$$

Where a suitable initial trial value for the argument is $X_{ns,i=1} = \left(\frac{b_{ns}X_{ns,fr}}{B_{ns,fr}}\right)$.

Stopping buses' practical capacity for the given non-stopping bus flow rate is then calculated according to **Equation 18**:

$$B_{s,p} = \frac{3600X_{la,p}N_{la}}{t_{la,net,p}} \tag{18}$$

Practical Saturation Frontier

Equation 15 reflects that operation of the station is limited by a practical saturation frontier, which we can further define as the relationship between non-stopping buses' practical capacity and stopping buses' practical capacity.

The theoretical minimum possible value of $B_{ns,fr}$ on this frontier corresponds to a theoretical loading area degree of saturation of 1.0, according to **Equation 19**:

$$B_{ns,fr,min} = B^*_{ns,fr}\left(\frac{\left(t_{re,fr} + t_d\right)}{t_{la,net,fr}}\right) \tag{19}$$

The relationship for stopping buses' practical capacity on this frontier, where $B_{ns,fr} \in \left(B_{ns,fr,min} \dots B^*_{ns,fr}\right)$ is defined according to **Equation 20**:

$$B_{s,fr} = \frac{3600N_{la}}{t_{la,net,fr}}\left(\frac{1-\left(\frac{B_{ns,fr}}{B^*_{ns,fr}}\right)}{1-\left(\frac{t_{re,fr}+t_d}{t_{la,net,fr}}\right)}\right) \tag{20}$$

Station operation on the practical saturation frontier would be highly volatile and is therefore not recommended.

Suitable Non-stopping Buses' Practical Degrees of Saturation

Equations 15 through 18 require specification of loading area practical degree of saturation, $X_{la,p}$ and non-stopping buses' practical degree of saturation, $X_{ns,fr}$ in order to calculate non-stopping buses' practical capacity and actual degree of saturation.

First, we consider non-stopping buses' practical degree of saturation. If this value is considered constant across all flow rates less than practical capacity, operating degree of saturation will be less than practical degree of saturation.

The general traffic facility that most closely approximates a BRT facility where buses cannot overtake is a two lane, two-way directional segment. HCM 2016 (*26*) stipulates a typical saturation flow rate of 1,700pc/h and contains a method to determine level of service on this type of facility, which is based upon estimation of percent time spent following and average travel speed considering both directions of travel, given the directional flow rates. However, this method is not suited to the low travel speed environment of a BRT facility at a station, where a posted speed limit of 50km/h applies in our testbed. Regardless of flow rate and estimated percent time spent following, the method returns a LOS E performance and is therefore unable to be used to define a suitable practical degree of saturation.

We instead consider the HCM 2016 (*26*) multi-lane highways method to estimate saturation flow rate and practical degree of saturation, using the speed – flow curves with LOS criteria on a per lane basis. On the Brisbane, Australia BRT network that is represented by our analytical testbed, non-stopping bus drivers are trained to pass a BRT station without exceeding the 50km/h posted speed limit. The HCM method does not contain a curve for this value as free flow speed. However, extrapolation from the family of speed – flow curves indicates a capacity of 1,500pc/h/ln for a 50km/h free flow speed. The method recommends a heavy vehicle adjustment of 1.5pc, so the extrapolated theoretical capacity and therefore saturation flow rate on the passing lane, $s_{ns} = 1{,}000$bus/h. Also, extrapolating from the curves, for a posted speed limit of 50km/h the level of service D/E threshold flow rate equals 1,000pc/h/ln, so the extrapolated non-stopping buses' practical maximum flow rate, $B^*_{ns,fr} = 667$bus/h. Adoption of a level of service D/E threshold therefore equates to a non-stopping buses' practical degree of saturation, $X_{ns,fr} = 0.667$.

Suitable Loading Area Practical Degree of Saturation

Second, we consider loading area practical degree of saturation. Along with its value, the assumption about whether loading area practical degree of saturation should remain constant with non-stopping buses' flow rate requires careful consideration. Bunker (*6*) discussed that processing of buses through a loading area of a bus stop has similar characteristics to operation of an unsignalized intersection. However, within the hour the loading area as a server is subject to less fluctuation than the head of the queue on a minor movement at an unsignalized intersection. The increase in upstream average waiting time with degree of saturation were noted as being less pronounced. However, waiting time upstream of a loading area at a BRT station can be more consequential than at an unsignalized intersection, because of the effects of bus queuing upon station and line operation.

Bunker (*6*) estimated upstream average waiting time according to **Equation 21**:

$$t_{w,la} = 600T\left((X_{la} - 1) + \sqrt{(X_{la} - 1)^2 + \frac{t_{la,net}X_{la}}{450T}}\right) \tag{21}$$

Where system time, $T = 1.0\text{h}$. Equation 21 is scalable. Therefore, where multiple loading areas exist, and assuming an average of utilization of all loading areas, the estimate of upstream average waiting time can be applied to the whole station. In Equation 21, for a given non-stopping buses' flow rate, $t_{la,net}$ will be constant irrespective of loading area degree of saturation. A detailed discussion is provided in *(6)* of how stochastic effects across operational parameters were incorporated into the formulation of **Equation 21**.

Rearranging Equation 21, an appropriate loading area practical degree of saturation assuming common utilization across all loading areas, is defined according to **Equation 22**:

$$X_{la,p} = \frac{\left(1 + \frac{t_{w,la,p}}{1200T}\right)}{\left(1 + \frac{2t_{la,net,p}}{3t_{w,la,p}}\right)} \tag{22}$$

Where $t_{w,la,p}$ is a specified upstream average waiting time and $t_{la,net,p}$ corresponds to a given non-stopping buses' adjusted flow rate.

Loading area practical degree of saturation should not cause excessive upstream average waiting time, particularly as non-stopping buses' flow rate approaches practical capacity. To determine non-stopping buses' practical capacity and associated loading area practical degree of saturation, we consider values of specified upstream average waiting time between 10s and 30s.

To further investigate the effect of specified upstream average waiting time, we estimate stopping buses' average queue length upstream of the station platform according to **Equation 23**:

$$Q_{av,s,p} = \frac{B_{s,p}t_{w,la,p}N_{la}}{3600} \tag{23}$$

Charting Practical Saturation Frontier

To chart the practical saturation frontier, we estimate the range of loading area practical degree of saturation using Equations 19 and 20 by varying $B_{ns,fr}$, rather than assigning a value according to Equation 22. We then estimate the range of stopping buses' practical capacity by substitution of the range of $t_{la,net,fr}$ into Equation 20 and the range of stopping buses' upstream average queue length by substitution of the range of $B_{s,fr}$ into Equation 23.

Flowcharts
The left hand panel in **Figure 2** illustrates the flowchart to estimate stopping buses' practical capacity and average upstream queue length as a function of non-stopping buses' flow rate and other necessary parameters, while the right hand panel illustrates the flowchart to chart the practical saturation frontier, using the BRT-PC model.

Analytical Testbed to Compare TCQSM and BRT-PC Models
For direct comparison, we determine capacity of a stylized station on the Brisbane, Australia BRT network using each of the TCQSM model based on Equation 1 and the BRT-PC model of Equations 4 through 23 under conditions where non-stopping buses have absolute priority over re-entering buses. We use a peak period mean dwell time of 20s (*6*) to reflect a typical BRT station. We assign the start-up component of clearance time equal to 10s for a standard bus (*27*). We estimate re-entry delay using values of 7.0s for critical headway and 3.3s for follow-up headway. The testbed BRT station contains three actual loading areas. We use a value of 2.60 effective loading areas according to TCQSM (*1*). The next section presents results.

RESULTS

Non-stopping and Stopping Buses' Practical Capacity and Degree of Saturation Calculations
Using Equations 2 and 3 re-entry delay, $t_{re,fr} = 6.1$ s. Using Equation 14 bus-bus interference time, $t_{bbi,fr} = 5.6$ s. Using Equation 5 loading area average total processing time per bus net of processing margin, $t_{la,net,fr} = 41.7$ s.

For an example specified practical upstream average waiting time of 20s, using Equation 22 loading area practical degree of saturation, $X_{la,fr} = 0.43$ and using Equation 15 non-stopping buses' practical capacity, $B_{ns,fr} = 561$ bus/h.

We use the left panel flowchart of Figure 2 to determine stopping buses' practical capacity and degree of saturation, as well as non-stopping buses' degree of saturation, across a range of non-stopping buses' flow rates, b_{ns}, between 0 bus/h and 667 bus/h.

Stopping Buses' Practical Capacity vs Non-stopping Buses' Flow Rate
The relationship between stopping buses' practical capacity and non-stopping buses' flow rate using the BRT-PC model for prescribed upstream average waiting times of 10s, 20s and 30s, along with TCQSM model results for a conservative failure rate of 2.5% are illustrated in **Figure 3**. TCQSM (*1*) recommends this value of design failure rate outside downtown areas "whenever possible, particularly when off-line stops are provided, as queues will block a travel lane whenever a bus stop failure occurs…".

The BRT-PC model curve is shown for each prescribed upstream average waiting time. As non-stopping buses' flow rate increases, both re-entry delay and bus-bus interference time increase, leading to an increase in loading area average total processing time per bus net of processing margin and a gradual decrease in stopping buses' practical capacity and degree of saturation.

The practical saturation frontier is also shown, which is calculated using the right panel flowchart of Figure 2. Stopping buses' practical capacity and degree of saturation reduces linearly, and dramatically so, to a value of zero when non-stopping buses' flow rate reaches maximum practical, $B^*_{ns,fr}$. This because the amount of time available to process any buses on the loading areas tends towards zero.

Stopping buses' practical capacity and degree of saturation are impacted markedly by prescribed upstream average waiting time. For instance, when there are no non-stopping buses, to limit upstream average waiting time to 10s, the loading areas will operate at a practical degree of saturation of 0.30, whereas to limit the average waiting time to 30s, the loading areas will operate at a practical degree of saturation of 0.58. This demonstrates the importance of setting an appropriate upstream average waiting time.

The relationship between stopping buses' design capacity and non-stopping buses' flow rate using the TCQSM model under a 2.5% failure rate is similar to the BRT-PC curve for a 30s upstream waiting time under low non-stopping buses' flow rate, but does not decrease with increasing non-stopping buses' flow rate as much as the BRT-PC model, because the TCQSM model does not account for the compressed non-stopping buses' flow rate witnessed by re-entering drivers.

On the practical saturation frontier, the effect of increasing processing margin dramatically reduces stopping buses' practical capacity towards zero at non-stopping buses' maximum practical flow rate. With this sharp reduction, operation is highly volatile with non-stopping buses' flow rate and needs to be avoided. However, the TCQSM model does not account for this frontier at all. This comparison demonstrates that both phenomena are significant in BRT station operation.

Figure 3 highlights that under the conservative 2.5% failure rate, TCQSM model stopping buses' design capacity is approximately twice the practical capacity estimated using the BRT-PC model for a specified 10s upstream average waiting time. This highlights that the TCQSM failure rate approach does not account for the significance of the effect of cascading delays due to horizontal queue formation as buses wait to enter available loading areas, due to stochasticity of parameters discussed earlier and in (*2*).

Stopping Buses' Average Upstream Queue Length vs Non-stopping Buses' Flow Rate

To investigate the effect of prescribed upstream average waiting time further, we estimate the stopping buses' average upstream queue length using Equation 23. **Figure 4** illustrates the relationship this queue length and non-stopping buses' flow rate using the BRT-PC model for prescribed upstream waiting times of 10s, 20s and 30s.

Stopping buses' upstream average queue length is affected profoundly by prescribed upstream average waiting time. For a given non-stopping buses' flow rate, upstream average queue length for a 20s upstream waiting time is approximately three times that of a 10s average waiting time, while average queue length for a 30s upstream waiting time is approximately six times that of a 10s average waiting time. It is crucial to prescribe a stopping buses' upstream average waiting time that does not cause excessive bus queues that spill out of the stopping lane upstream of the platform and diverge taper, into the passing lane.

For stations on the Brisbane, Australia BRT network represented by the analytical testbed, the stopping lane typically extends 20m back from the rear of the platform (Figure 1). The diverge taper length varies depending on approach speed. The 20m stopping lane extension plus a portion of the diverge taper that accommodates a bus width of 2.4m would just hold a queue of two, 12.3m rigid buses. According to Figure 4, a prescribed upstream average waiting time of 10s would result in a stopping buses' upstream average queue that would readily be stored in the available geometry, without blocking non-stopping buses. However, a prescribed upstream average waiting time of 20s would result in queuing that would, on average, block non-stopping buses, which may be unacceptable especially on higher speed approaches. Under such circumstances a prescribed upstream average waiting time of 30s would clearly be unacceptable.

It is noteworthy that stopping buses' upstream average queue length reduces moderately as non-stopping buses' flow rate increases. This is due to the moderate reduction in stopping buses' practical capacity and its direct effect upon average upstream queue length according to Equation 23.

On the practical saturation frontier, stopping buses' upstream average queue length reduces sharply towards zero at the point where non-stopping buses' maximum practical flow rate is reached, corresponding to zero working capacity for stopping buses. Again, with this sharp reduction, operation is highly volatile with non-stopping buses' flow rate and needs to be avoided.

This examination of stopping buses' upstream average queue lengths considers horizontal queuing. It is important to note that, at times when queues exceed average, additional geometry may be necessary to store stopping buses mixed in queue. It may be appropriate to consider a non-stopping buses' upstream design queue length, or a more conservatively prescribed upstream average waiting time to avoid non-stopping buses from being queued.

Estimation of this upstream bus queuing is not possible using the TCQSM model. This examination highlights the need for our BRT-PC model to analyze and design for this crucial aspect of BRT station operation.

CONCLUSIONS

Our study developed the BRT-PC model to estimate BRT station stopping buses' practical capacity as a function of non-stopping buses' flow rate as well as traditional parameters of the TCQSM model. By associating a practical saturation frontier with non-stopping buses, reflecting that re-entering drivers witness a compressed non-stopping buses' stream, and incorporating stopping buses' practical degree of saturation as a function of prescribed upstream average waiting time, the BRT-PC model provides superior insight into station operation than the TCQSM model. We related stopping buses' practical degree of saturation directly to processing margin, which unlike the TCQSM model operating margin, accommodates all stochastic influences that may arise during the processing of a stopping bus.

We quantified non-stopping buses' practical saturation flow rate and practical degree of saturation by considering the analogous system of a low speed, multilane highway lane operating at a level of service D/E threshold. Our BRT-PC model estimates stopping buses' practical degree of saturation as a function of a prescribed upstream average waiting time by considering the analogous system of delay at an unsignalized intersection minor movement.

We applied an analytical testbed based on a stylized station of the BRT network of Brisbane, Australia illustrated in Figure 1 to compare results using the TCQSM and BRT-PC models with typical values of input parameters. The relationship between stopping buses' design capacity and non-stopping buses' flow rate estimated according to the TCQSM model under a conservative 2.5% failure rate is similar to the BRT-PC curve for a 30s upstream average waiting time under low non-stopping bus flow rates, but does not decrease with non-stopping bus flow rate as much as the BRT-PC model, highlighting that the failure rate approach does not account for the numerous stochastic influences that result in the significant effect of cascading delays due to horizontal queue formation as buses wait to enter available loading areas.

The BRT-PC model reveals that stopping buses' practical capacity and degree of saturation are impacted markedly by prescribed upstream average waiting time. To investigate further, we estimated stopping buses' upstream average queue length. When non-stopping buses' degree of saturation is less than the practical limit, stopping buses' upstream average queue length is affected profoundly. For a given non-stopping buses' flow rate, average queue length for a 20s upstream waiting time is approximately three times that of a 10s average waiting time, while average queue length for a 30s upstream waiting time is approximately six times that of a 10s average waiting time.

It is crucial to prescribe a stopping buses' upstream average waiting time that does not cause excessive queues that spill back into the passing lane. For a 20s average dwell time, we found that a 10s value would result in an average queue that would readily be stored in the available geometry, without blocking non-stopping buses. However, a 20s value would result in an average queue that would block the passing lane, which may be unacceptable especially on higher speed approaches, while a 30s value would be clearly unacceptable.

Accurate estimation of upstream bus queuing is not possible under the TCQSM model. This highlights the need for our BRT-PC model to analyze and design for this crucial aspect of BRT station operation, which is a daily occurrence at several busy stations on the BRT network of Brisbane, Australia.

A limitation of this study is that we assumed absolute priority of non-stopping buses over stopping buses during the re-entry process in our testbed analysis and comparison. Future research will examine how shared priority can be modelled effectively and whether it makes a difference to station operation. Another limitation is that we are still to consider queuing impacts on non-stopping buses when non-stopping bus queues exceed available storage, along with specification of design upstream queue length. Also, we directly applied the value of number of effective loading areas from the TCQSM, which does not account for platooned arrivals and processing for off-line loading areas. It will be useful to investigate further whether platooning affects station performance.

This study is limited to the standard station configuration of the Brisbane BRT network illustrated in Figure 1 having three off-line loading areas. It would be expected to be reasonable to directly apply our BRT-PC model to stations containing either two or four off-line loading areas; however, the model in its present form is not applicable to on-line configurations.

It will be appropriate to acquire field data across a range of BRT station types and a range of regions globally to verify the BRT-PC model with upstream average waiting time under a wide range of operating conditions and to compare results with those determined using the TCQSM model, in order to inform recommendations regarding any revisions or additions to the TCQSM methodology.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: J.M. Bunker, F. Hisham; data collection: F. Hisham, J.M. Bunker; analysis and interpretation of results: J. Bunker, F. Hisham; draft manuscript preparation: J.M. Bunker, F. Hisham. All authors reviewed the results and approved the final version of the manuscript.

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FIGURES

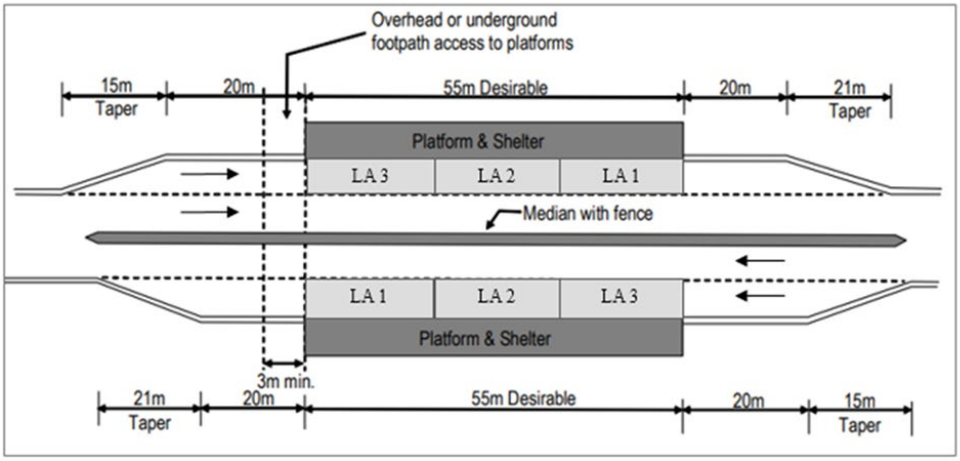

Figure 1 Typical BRT station layout on South East Busway, Brisbane, Australia (*5*)

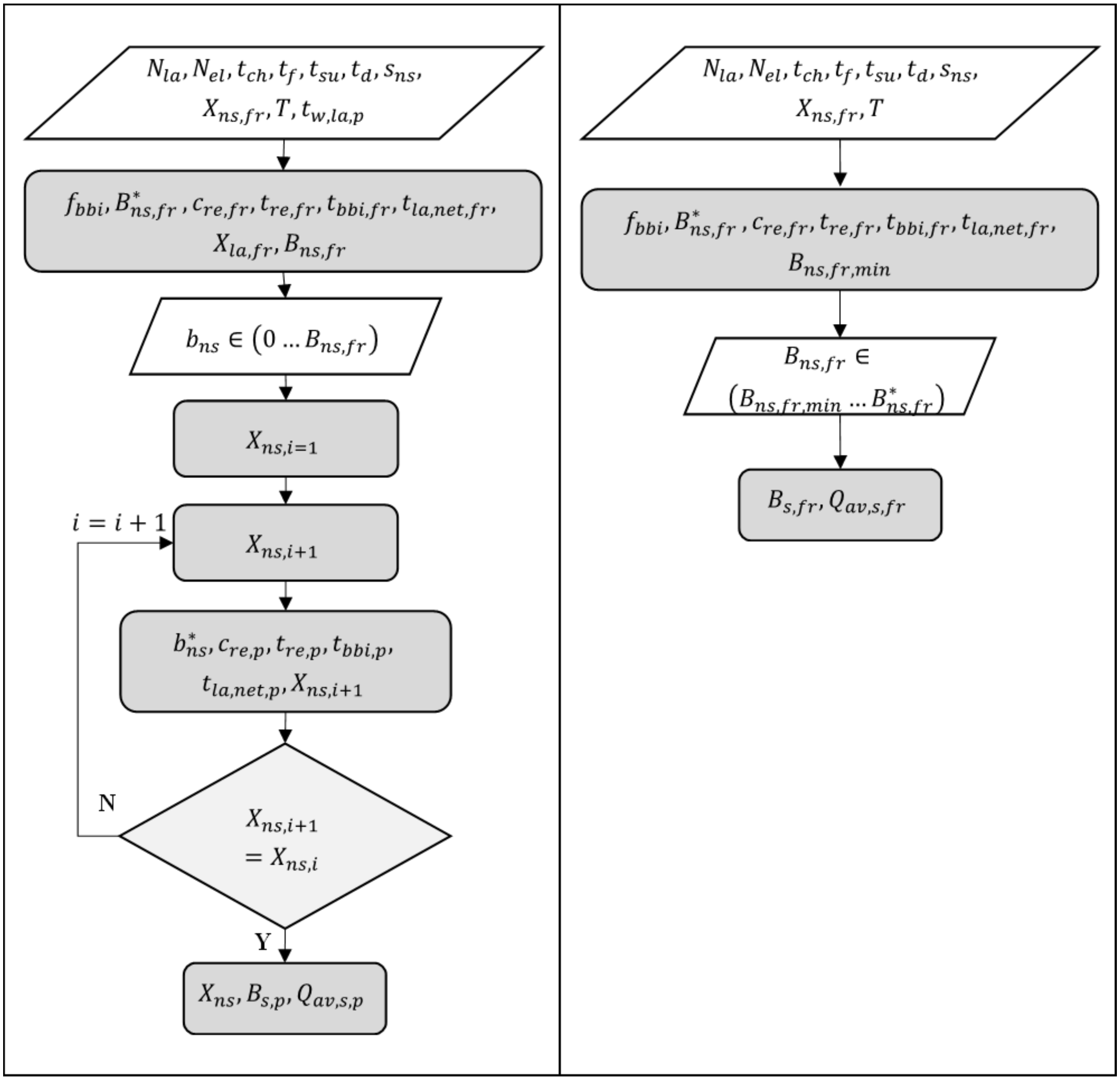

Figure 2 BRT-PC Model Estimatation of Stopping Buses' Practical Capacity and Average Upstream Queue Length (left panel) and Practical Saturation Frontier (right panel)

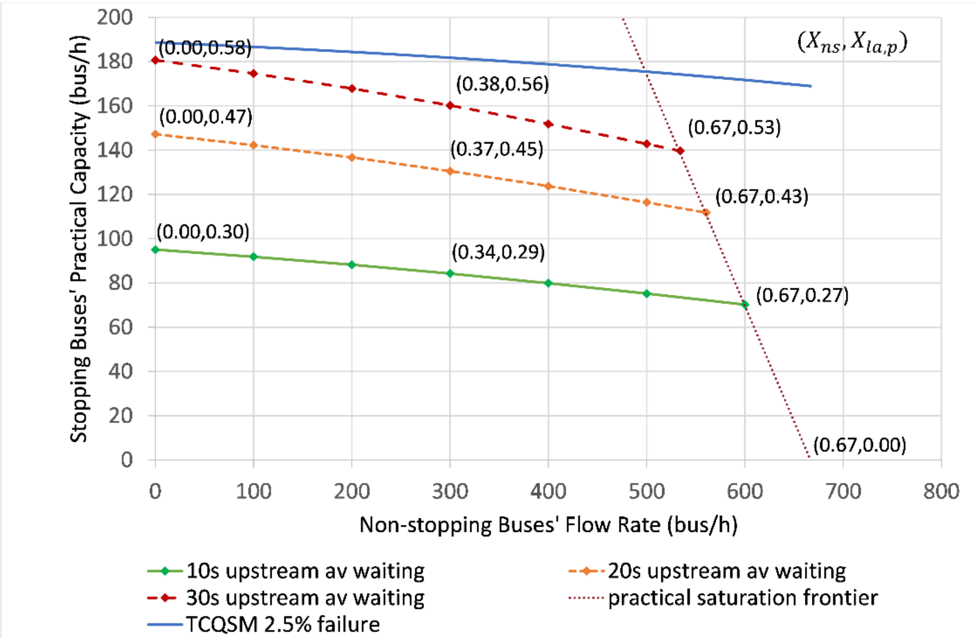

Figure 3 Testbed BRT Station Stopping Buses' Practical Capacity vs Non-stopping Buses' Flow Rate (BRT-PC and TCQSM Models)

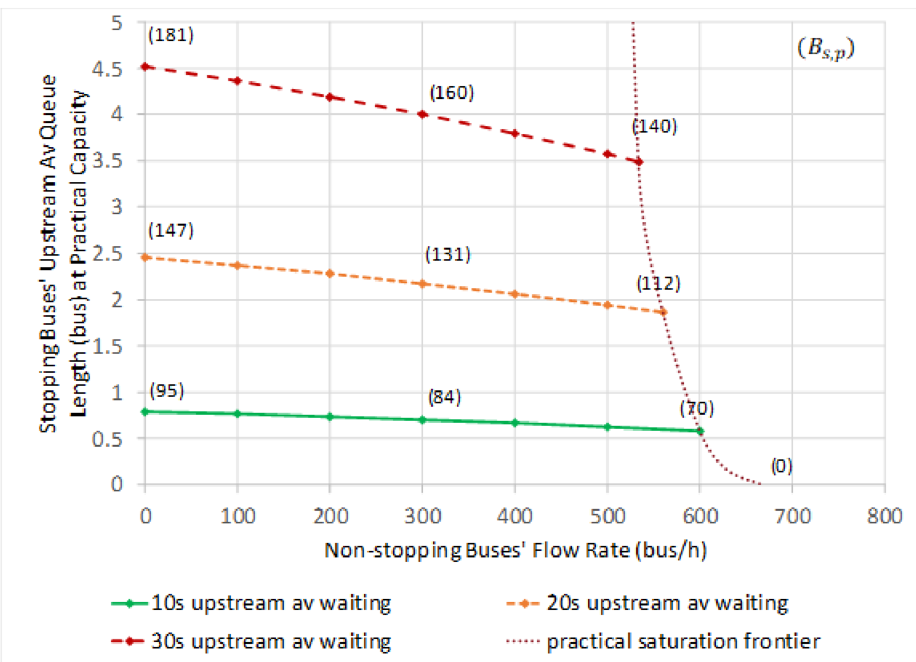

Figure 4 Testbed BRT Station Stopping Buses' Upstream Average Queue Length at Practical Capacity vs Non-stopping Buses' Flow Rate (BRT-PC and TCQSM Models)