Technical Note

Subject:	Capacity Calculations
Project:	City Centre Bus Reference Case
Our file:	NZ 1982

Our file:	NZ 1982	Date:	25 November 2015
Status:	Draft	Prepared by:	RLG

1. Methodology: Stochastic Queueing Theory

The methodology for calculating the required bus stop capacity for a given volume of bus service was developed on the basis of a steady but irregular stream of buses being bunched into groups by traffic lights. This allowed the use of stochastic queueing theory (Rouphail, Tarko & Li, n.d.; Troutbeck & Brilon, n.d.; Transit Cooperative Research Program, 1996) to determine the number of buses we expect to be queued at a traffic signal when the light turns green, and therefore how many buses we can expect to arrive together at the next bus stop downstream from the traffic light.

The inputs required for calculating the probability that a given number of buses join the queue during one signal cycle are:

1. The number of buses per hour in the corridor, i.e., arrival rate or frequency, q;
2. The number of buses queueing during one signal cycle, n; and
3. The signal cycle time, t.

The probability that n buses join the queue during a signal cycle is given by the following equation:

$$P_n(t) = \frac{(qt)^n e^{-qt}}{n!}$$

This calculation assumes that:

↘ The arrival of buses at a signalised intersection is randomly distributed, i.e., it can be represented by a Poisson or negative exponential distribution;
↘ Buses travel in dedicated bus lanes, and are therefore not delayed by or intermingled with general traffic queues;
↘ All buses at the traffic signal will use the same stop downstream;
↘ There is no limit to the number of buses that can queue while the signal is red;
↘ All buses are cleared from the queue while the signal is green; and
↘ The queueing discipline is FIFO (first in, first out), i.e., buses depart from the queue in the same order that they arrive.

We also calculated the cumulative probability that no more than n buses will join the queue during one signal cycle by summing probabilities from 0 to n.

2.   Calculating Capacities: Inputs and Assumptions

The methodology outlined above was used to ascertain bus infrastructure requirements for city streets at peak bus volumes. In order to determine the number of loading areas required to handle a given frequency of bus service, the following assumptions were made:

- The signal cycle time, t, is two minutes;
- All buses will exit the stop within two minutes, i.e., before the next platoon of buses arrives; and
- The bus stop must be able to handle the expected number of buses arriving 90% of the time.

By calculating cumulative probabilities using a range of values for bus frequency (q) and number of buses in the queue (n), we generated a table showing the probability that no more than n buses would arrive in the same two-minute period for each value of q. This table can be used to determine the maximum number of buses that we need to provide stopping space for in order to accommodate a given bus frequency 90% of the time. In other words, the table allows us to answer the question "how many loading areas do we need for the peak frequency to be accommodated 90% of the time (while accepting some congestion 10% of the time)?"

For example, if 16 buses per hour use a corridor, the probability of zero buses arriving at a signalised intersection during a two-minute period is 59%, while the probability of one bus arriving is 31%, so there is a 90% probability that no more than one bus will arrive at the intersection per two-minute signal cycle. Put another way, if a bus stop contains a single loading area, there is a 10% probability that more than one bus will arrive to use the stop from one two-minute signal cycle if 16 buses per hour are using the corridor.

Note that this methodology assumes all buses arriving at a stop have come from the same corridor upstream. However, buses may arrive from two (or more) separate approaches, e.g., westbound buses on Wellesley Street may come from either Symonds Street or Grafton Road. When this occurs, bus volumes from the two approaches must be treated independently, i.e., bus stop capacities must be calculated as though buses from each approach will use separate stop groups in the downstream corridor. While this strategy arises from the simplifying assumptions in the methodology used, it is also preferred from a customer service perspective because it improves legibility of the network.

2.1. Signal Cycle Time

Signal cycle time is one of the key inputs to this calculation, and we assumed a cycle time of 2 minutes, or 120 seconds. If we use a shorter cycle time, the number of loading areas required to handle each group of buses would be reduced, but there would be less time available for buses to drop off and pick up passengers before the next group of buses arrive. Conversely, if we assume a longer cycle time, larger bus stops would be required. Note that some signal cycles in the city centre are currently as long as 3 minutes due to pedestrian priority, but shorter signal times could be used to limit the number of buses queueing and arriving at a stop at once.

Table 1 shows the number of loading areas required at a stop to handle buses released from an intersection with signal cycle times of 90 seconds, 120 seconds and 180 seconds. For any given bus stop capacity, increasing signal cycle time from 90 seconds to 120 seconds reduces the bus volumes that can be handled by a stop by ~25%. Likewise, for a given bus volume, longer signal cycle times result in a longer queue of buses forming, thus necessitating an increased number of loading areas per stop. For example, a corridor with 60 buses per hour would require a triple stop

with a 90-second signal cycle, a quadruple stop with a 120-second signal cycle, and a quintuple stop with a 180-second signal cycle.

Table 1: Impact of signal cycle time on bus stop capacity.

Number of loading areas per stop per direction	Maximum corridor volume (Buses per hour per direction)		
	90 seconds	120 seconds	180 seconds
1	21	16	10
2	45	33	22
3	71	53	35
4	98	74	49
5	127	95	63
6	157	118	78
7	188	141	94
8	219	164	109
9	251	188	125
10	283	212	141

It is important to note that our calculations of required bus stop capacity assume bus dwell time at the stop is always less than the signal cycle time. The TCQSM developed by the Transit Cooperative Research Program (2013) provides a default dwell time of 60 seconds for downtown stops, indicating a maximum dwell time of 90 seconds or longer is sufficient. We assume that buses will travel in dedicated bus lanes in city centre corridors, so there will be no delay due to re-entering general traffic flow.

2.2. Bus Stop Failure Rate

Our calculation of required bus stop capacity assumes that the number of loading areas provided will be able to handle the corridor bus frequency 90% of the time. This corresponds to a 10% failure rate, i.e., 10% of the time a bus will arrive at a stop to find that all the loading areas are already full. Bus stop failure typically occurs when the number of buses using a stop is approaching the stop capacity. A high bus stop failure rate causes operational problems, but it is also associated with a more efficient use of bus stop capacity because a new bus is available to move into the stop as soon as the current bus departs. Therefore, the TCQSM recommends high failure rate between 7.5% and 15% in downtown areas in order to balance the negative impacts on bus reliability and speed with the increased throughput required for busy bus corridors (Transit Cooperative Research Program, 2013). The 10% failure rate used for city centre corridors in our calculations is in line with this recommendation.

AT requested that a 5% failure rate also be considered. Decreasing the failure rate to 5% would reduce the incidence of congestion and increase reliability, but it would also increase the bus infrastructure requirements. Table 2 compares the corridor bus volumes that can be handled up to 85%, 90% or 95% of the time by a given number of loading areas (i.e., a failure rate of 15%, 10% or 5%, respectively).

Table 2: Impact of bus stop failure rate on bus stop capacity.

Number of loading areas per stop per direction	Maximum corridor volume (Buses per hour per direction)		
	15% failure rate	10% failure rate	5% failure rate
1	20	16	11
2	40	33	25
3	61	53	42
4	84	74	60
5	107	95	80
6	131	118	100
7	155	141	121
8	180	164	143
9	205	188	165
10	230	212	188
11	256	237	211

Prescribing a lower failure rate means a smaller volume of buses can be handled by a stop of a given size. Consequently, if failure rates were decreased from 10% to 5%, larger bus stops would be required to service a corridor carrying a given volume of buses. For example, a corridor with 61 buses per hour in one direction requires a quadruple stop using a 10% failure rate; the required number of loading areas increases to five with a 5% failure rate, and decreases to three with a 15% failure rate.

2.3. Spatial Requirements

2.3.1. Bus Stop Dimensions

This appendix has so far dealt with the *number* of loading areas required to handle a given corridor volume, but not the *space* required for the stop. The spatial requirement of bus stops is the key determinant as to how many buses a given corridor can accommodate.

The Transit Cooperative Research Program (1996) provides the following guidelines for bus stop dimensions:

- A 15 m loading area per standard 12 m bus (with no additional separation specified between loading areas);
- A 15 m no-parking zone for lead-in and lead-out, giving a minimum total length for inline stops of
  - 27 m for far-side stops,
  - 30 m for near-side stops, and
  - 45 m for mid-block stops; and
- A generous 50 m lead-in and lead-out for indented stops, with an additional 55–75 m for acceleration and deceleration.

Similarly, the NSW State Transit Bus Infrastructure Guide recommends a minimum total length of 30 metres for a 12.5 m standard bus, including an 11.5-metre lead-in and 6-metre lead-out. The same lead-in and lead-out dimensions are recommended for individual loading areas within a stop, except where buses are not required to move independently, in which case a minimum

separation of 6 metres between buses is required (State Transit Authority of New South Wales, 2011).

However, a survey of 48 transit agencies across the United States found that typical stop dimensions tend to be much smaller than the guidelines. The length of a standard bus stop was usually 18–24 metres, although it should be noted that most agencies surveyed did not base stop lengths on the number of buses using the stop (Transit Cooperative Research Program, 2015).

The Bus Reference Case assumes a nominal 12-metre bus length. Two scenarios are considered with regard to bus stop dimensions:

1. Minimise Spatial Requirements.
    This scenario aims to minimise the cost of bus stops by minimising spatial requirements. The values assumed for bus stop spacing are:

    ↘   3 m separation between buses;
    ↘   3 m buffer at the end of inline stops;
    ↘   12 m lead-in buffer for indented stops;
    ↘   6 m lead-out buffer for indented stops; and
    ↘   6 m separation between stops.

    Note that these dimensions have been increased from those presented in earlier versions of the Bus Reference Case report. The lead-in and lead-out dimensions are informed by NSW State Transit's guidelines (State Transit Authority of New South Wales, 2011), while the separation is based on field observations, as discussed below. The following are key attributes of this scenario:

    ↘   Reduced spatial dimensions result in reduced land costs.
    ↘   Smaller bus stop dimensions are likely to be preferable from an urban design perspective.
    ↘   Walking distances would be reduced for passengers moving from their waiting position to board a bus further along the stop.
    ↘   Bus stops are assumed to not have spillover/blocking at least 90% of the time during the peak, as described in Section 2.2; however, we note that allowing bus stop failure to occur up to 10% of the time is not desirable from an operations perspective.

2. Prioritise Bus Operations.
    This is Auckland Transport's preferred scenario, which aims to minimise delays at bus stops as a result of buses spilling over or extending into adjacent bus lanes or general traffic lanes. Auckland Transport's Bus Services group uses the following dimensions as guidelines for bus stop design:

    ↘   15 m long loading areas;
    ↘   15 m lead-in to indented bus stops;
    ↘   9 m lead-out of indented bus stops; and
    ↘   9 m separation between buses within double, triple or longer stops.

    Key attributes of the scenario are:

    ↘   Higher spatial requirements;
    ↘   A likely increase in the distance passengers will have to walk within the length of a stop and from one stop to another; and
    ↘   Reduced likelihood of bus stop failure by effectively increasing the number of buses that can utilise the stop above the design capacity; however, if the desired 9-metre bus

separation is maintained in practice then the improvement in bus stop failure rate would be negligible.

Table 3 presents the total bus stop dimensions for the two scenarios for stops containing up to three loading areas. Additional space is required for indented stops in both scenarios to allow buses to enter and exit the stop. The larger stop dimensions in the Prioritise Bus Operations scenario substantially increase the size of the stops compared to the Minimise Spatial Requirements scenario.

Table 3: Bus stop dimensions for two scenarios, Minimise Spatial Requirements and Prioritise Bus Operations.

Stop type	Number of loading areas per stop	Stop length (m)	
		Minimise Spatial Requirements	Prioritise Bus Operations
Inline	1	15	15
	2	30	39
	3	45	63
Indented	1	30	39
	2	45	63
	3	60	87

Requiring a 9-metre separation between buses—as in the Prioritise Bus Operations scenario—enables buses to enter and exit bus stop loading areas independently. However, one of the key assumptions underlying this analysis is that buses form platoons at signalised intersections and thus arrive at and depart from bus stops in groups. Thus, this assumption mitigates the requirement for a large separation between loading areas and enables the use of a smaller 3-metre gap between buses, as in the Minimise Spatial Requirements scenario.

Observations on key bus corridors in the city centre also support the suitability of a 3-metre separation between buses. For example, at a busy stop on Symonds Street during the morning peak (between Mount Street and St Paul Street), buses can be seen pulling into the stop with a gap of approximately 2.5–3 metres between buses, as shown in Figure 2-1. Buses often departed the stop in platoons, but they also had sufficient space to pull out into the bus lane independently of the bus in front; despite the sharp angle of the turn causing buses to swing out into the adjacent lane, no interference with general traffic was observed. Similar behaviour was also observed on Fanshawe Street along Victoria Park during the evening peak.

Figure 2-1: Buses pulled into a stop on Symonds Street during the morning peak.

It is worth noting that the exact stop dimensions at a specific location will vary depending on the situation and will be determined as part of a detailed design or business case. The Transit Cooperative Research Program (2015) observed that the recommended stop length cannot always be obtained at the preferred location for a bus stop; in this situation, transit agencies will commonly look for an alternative site nearby or make do with a shorter stop. In Auckland, it is likely that the actual design dimensions will fall on a spectrum between the two scenarios presented above, depending on factors such as funding and spatial constraints. For example, the Prioritise Bus Operations scenario recommends a length of 87 metres for an indented triple stop, but a stop of this length may simply not fit on many of the blocks in Auckland's city centre.

2.3.2. Preferred Bus Stop Length

Double or triple stops are preferred from an operational perspective. The assumption that all buses in one platoon exit the stop before the next platoon of buses arrives holds best when stops are divided into groups of two or three loading areas, so that buses are less likely to be held up by the movements of other buses and are more able to enter and exit a stop within the specified time period. In addition, in situations where bus arrivals and departures do not consistently occur in platoons, quadruple or quintuple stops cannot be utilised as efficiently as two separate double or triple stops (Transit Cooperative Research Program, 2013).

Stops with no more than three loading areas are also considered more desirable from a user perspective. At a quadruple stop, for example, passengers waiting at the front of the stop may have to run 50 metres or more to reach their bus if it pulls into the final loading area while the first three loading areas are occupied. Furthermore, at this distance passengers may not be able to read the bus headsign to determine whether it is their bus that has arrived. Therefore, quadruple or quintuple stops provide a lower level of customer service than double or triple stops.

References

Rouphail, N., Tarko, A. & Li, J. (n.d.). Traffic Flow at Signalized Intersections. In N. Gartner, C. J. Messer & A. K. Rathi (Eds.), *Revised Monograph on Traffic Flow Theory*. Retrieved from https://www.fhwa.dot.gov/publications/research/operations/tft/ on 17 November 2015.

State Transit Authority of New South Wales (2011). *Bus Infrastructure Guide.* Retrieved from http://www.statetransit.info/publications/ on 19 November 2015.

Troutbeck, R. J. & Brilon, W. (n.d.). Unsignalized Intersection Theory. In N. Gartner, C. J. Messer & A. K. Rathi (Eds.), *Revised Monograph on Traffic Flow Theory*. Retrieved from https://www.fhwa.dot.gov/publications/research/operations/tft/ on 17 November 2015.

Transit Cooperative Research Program (2015). *TCRP Synthesis 117: Better On-Street Bus Stops – A Synthesis of Transit Practice.* Washington, DC: Transportation Research Board. Retrieved from http://www.trb.org/Main/Blurbs/172376.aspx on 19 November 2015.

Transit Cooperative Research Program (2013). Bus Transit Capacity. In *TCRP Report 165: Transit Capacity and Quality of Service Manual* (3rd ed.). Washington, DC: Transportation Research Board. Retrieved from http://www.trb.org/Main/Blurbs/169437.aspx on 22 January 2015.

Transit Cooperative Research Program (1996). Street-Side Factors. In *TCRP Report 19: Guidelines for the Location and Design of Bus Stops.* Washington, DC: National Academy Press. Retrieved from http://www.trb.org/Main/Blurbs/153827.aspx on 17 November 2015.