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Improving Capacity Estimation of High Volume On-Street Bus Facilities with Yield-to-Bus Rule

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Abstract

Effectiveness of an on-street bus facility depends on the general traffic volume that shares the lane with buses. The aim of this study is to better understand performance of an on-street bus facility by relating bus stop capacity with the adjacent lane traffic volume. The Transit Capacity and Quality of Service Manual (TCQSM) methodology estimates facility bus capacity based on critical stop operation. The theory is based on re-entry delay approach, where it is assumed that buses wait at the bus stop until there is no general traffic movement or queuing in the adjacent traffic lane. However, this theory does not reflect the influence of yield-to-bus (YTB) rule. Therefore, this research provides an improved understanding of critical bus stop operation on high volumes on-street bus facilities where the YTB rule applies. A microscopic simulation model is developed to model an off-line bus stop with two loading areas. The model is then used to observe bus stop capacity variations with increasing adjacent lane traffic volume. Two case scenarios are presented, one being the case where the bus stop is away from a signalized intersection and the second is the case where the bus stop is upstream of the signalized intersection. The simulation model demonstrates that inclusion of YTB rule allocates higher bus stop capacities in both cases. The model also shows that higher bus capacities are achievable due to elimination of re-entry delay.

Keywords- Bus stop capacity, on-street bus operation, yield-to-bus rule, YTB , re-entry delay, clearance time, bus processing time

1. Introduction

The success of an on-street bus (OSB) facility is highly dependent on the interaction buses have with other forms of traffic. OSB facilities includes arterial roads where the buses and other vehicles share the same lanes. When the lane carries a high volume of traffic, the interaction between buses and general could affect the capacity and quality of service of the bus facility. In order to understand and manage such a facility it is essential to understand the operation of its critical bus stop.

The Transit Capacity and Quality of Service Manual (TCQSM) (Kittelson and Associates, 2013) includes a deterministic design capacity methodology for a critical bus stop. The critical stop is that which has the lowest bus capacity, such that it governs the capacity of the bus facility (Jaiswal et al., 2010). The methodology was developed to properly estimate the achievable capacity with regard to operation of the critical bus stop. In the case of an off-line bus stop, the methodology includes a re-entry delay to represent the delays that could occur due to general traffic movement. The re-entry delay is calculated assuming that buses wait at the bus stop until there is no general traffic movement or queuing in the adjacent traffic lane past the bus stop. If there is an adjacent lane general traffic queue present, then the buses wait until the queue is cleared. If general traffic movement is occurring, buses must wait until they find a suitable gap in the adjacent general traffic lane. However, the theory does not reflect conditions where the yield-to-bus (YTB) rule applies. The aim of this study to better understand critical bus stop performance for off-line bus stops on high volume OSB facilities where YTB rule applies.

To achieve the study aim, the current literature on bus facility capacity and relationship with YTB laws were reviewed and are addressed in the next section. Existing theory to determine the theoretical critical bus stop capacity is provided in section 3. Section 4 presents the methodology of this study through development of a microscopic simulation model. Implementation of the microscopic simulation is demonstrated by two case study scenarios in section 5. This is followed by section 6, which demonstrates the impacts of high traffic volume on critical bus stop capacity. This paper concludes with section 7 and section 8, by offering discussions and conclusions for further research.

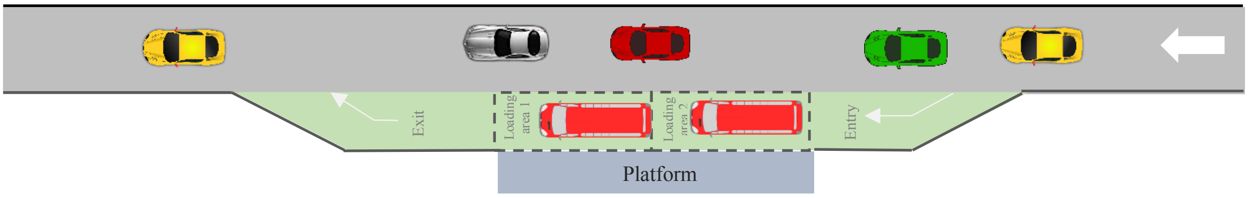
2. Literature Review

Numerous approaches were found in literature that focused on effects of high traffic volumes on bus stops. Some studies were conducted on the location (Ibeas et al., 2010, Gu et al., 2014), design (Szeto and Wu, 2011) and operations (Gu et al., 2011) of bus stops. However, capacity estimation of a bus stop needs to be given more importance because it is the critical stop that governs the capacity of the whole transit facility (St. Jacques and Levinson, 1997).

Many influences have been identified in previous research that affect bus stop capacity. Dwell time and clearance time are two such primary influences. Dwell time is a function of three contributing factors; numbers of boarding and alighting passengers, time required to open and close doors and time taken to process each passenger exchange. Clearance time is highly correlated with traffic operations and buses' mechanical performance. Further influences include signalized intersection red time periods, blockage by general traffic of the lane used by buses to process through the bus stop, along with interference between buses at the stop.

Dwell time at a bus stop will be affected by the layout of the bus stop. According to the Transit Capacity and Quality of Service Manual 3rd edition (TCQSM), bus stops can be categorized into two types; online bus stops and off-line bus stops. Online bus stops are the simplest form of bus stops, which are located adjacent to the curb. Lin et al. (2011) conducted research on improving capacity for exclusive bus lanes consisting of on-line bus stops. They found that moving the bus stop upstream of an intersection could increase capacities by 20% and that larger signal cycle times tend to reduce capacity. However, it is not found to be efficient due to traffic delays that can be caused by a dwelling bus (Lin et al., 2011).

Figure 1: Layout of an off-line bus stop (left hand travel)



Off-line bus stops are separated from the traffic lanes in order to provide convenience to boarding and alighting passengers (Fitzpatrick et al., 1996). At off-line bus stops, adjacent lane general traffic can pass without obstruction while a bus is dwelling. They are suitable at locations with high traffic volume, high speed roadways or sections with a high number of boarding and alighting passengers.

Figure 1 demonstrates a typical layout of an off-line bus stop located on an arterial road with an adjacent general traffic lane shown. It consists of three components; Entry area, passenger serving area, and exit area. The entry area facilitates the buses to enter a bus stop from the curb lane and the exit area facilitates the front-most bus to leave the bus stop to merge into the traffic on to the curb lane. Apart from locations where the YTB rule is in place, merging into the adjacent traffic lane can take a considerable amount of time because the driver needs to find an acceptable gap. For a lane with high traffic volume, this can be complex because of the increased difficulty in finding a suitable gap to re-enter into the traffic. Because of this unique interaction among buses and the adjacent lane traffic, clearance time of an off-line bus stop, which incorporates re-entry delay, should have a significant impact on the capacity of the bus stop.

Meng and Qu (2013) carried out a study to estimate the dwell time of an off-line bus stop using a probabilistic approach. They chose a case study station where buses are obliged to serve passengers more than once. Once the bus completes dwelling at the station, it moves to the exit area to find that the adjacent lane with high volume has taken up the lane capacity. Therefore, the bus must wait for a longer time at the exit area until it finds a suitable gap to merge into. During this time, when passengers arrive at the station, buses are forced to serve the passengers depending on the arrival rate. The research concluded that, even though an off-line bus stop facilitates adjacent lane traffic flow, it can significantly increase buses' re-entry delay due to the difficulty of finding an acceptable gap. However, they found that giving way (yielding) to buses at the exit of the bus stop has the potential of reducing the clearance time from 30% to 6.68%. This scheme was implemented in Singapore as "Mandatory Give Way to Buses" in 2008, giving greater priority to buses at 332 off-line bus stops. At a bus stop with mandatory give-way (MGW), motorists reduce speed and watch for exiting buses and come to a complete stop before the give-way sign and then return to speed once the bus has re-entered from the bus stop. The scheme showed that in some cases, the re-entry delay of buses from the bus stop reduced by 73% after the implementation (Haque et al., 2013).

Give way to buses has been implemented, predominantly in the USA. King (2003) investigated the use and experience of YTB laws implemented in British Columbia, California, Florida, Oregon and Washington in North America. Zhou et al. (2011) assessed the impacts of YTB laws in Florida and highlighted that YTB behavior depends on location of the bus stop, hourly traffic volume, number of lanes, speed environment and public attitude towards buses at a specific location. Hyde and Smith (2017) quantified the economic and other benefits of YTB rules for bus services in New Zealand. They established a relationship between number of cars and the delay to buses for locations where YTB rule applies, by conducting a video data analysis. They found out that average delay to buses exiting the bus stop equates to 5.69s and law changes to other road users are concluded to be marginal or negligible. The results also showed that, buses experienced re-entering delays at 25.45% of the stops, Even though among the 280 movements recorded, 14.3% benefitted from the YTB rules, the conclusion is case dependent. However, studies conducted on quantifying the benefits to stop bus capacity has been rare.

The current theoretical methodology presented in the Transit Capacity and Quality of Service Manual (TCQSM) (2013) incorporates the influence of bus stop location and bus's mechanical performance in its methodology to estimate bus stop capacity (Kittelson and Associates, 2013). The bus's mechanical properties are taken into consideration as the "start-up time" component of the clearance time. This component is obtained by the addition of time taken for one bus to replace another bus in the loading area. The second component of clearance time is defined as the "re-entry delay", which is the time taken for the adjacent lane general traffic queue formed by an adjacent traffic signal to clear plus the time taken for the bus driver to find a suitable gap and to merge into the adjacent lane traffic.

Studies have been conducted on impacts of off-line bus stops on speed of traffic (Koshy and Arasan, 2005), effects of bus stop design on arterial road operation (Fitzpatrick et al., 1996), delay at a bus stop caused by a downstream signal intersection (Wong et al., 1998) and capacity reduction caused by the combined effects of signalized intersection and bus stop (Zhao et al., 2007). However, research about the combined performance at off-line bus stops in terms of both stop bus capacity and adjacent lane traffic capacity has been scant.

This study addresses the major findings of the literature review. First, existing deterministic models do not allow for the YTB re-entry situation either through a reduction in re-entry delay or the consequential impediment on adjacent lane traffic capacity (King, 2003). Therefore, this study will instead develop a microscopic simulation model that reflects these aspects of critical bus stop operation for two location cases; away from any signalized intersection influence, and upstream of a signalized intersection. Second, priority re-entry of buses has the potential to increase bus stop capacity, however in achieving this there will necessarily be an impact upon the adjacent lane general traffic. This impact has not been sufficiently addressed in the literature. For this reason, this study will establish a relationship between critical bus stop capacity and the adjacent lane general traffic capacity under operation with the YTB rule.

3. Theoretical Model of Vehicle Operation at a Bus Stop

TCQSM (2013) (Kittelson and Associates, 2013) presents the standard methodology to estimate theoretical capacity of a bus facility on the basis of the critical bus stop.

A loading area is defined as a section of the stop which is designated for a single bus to stop, dwell and serve passengers. This study is concerned with an off-line bus stop similar to Figure 1, whereby vehicles cannot overtake except at the passing lane available at the bus stop. Our testbed includes a linear platform with two loading areas in series.

According to TCQSM (2013) service time per bus per loading area is defined to be the addition of clearance time (s), dwell time component during green time (s) and the operating margin (s) (extra time allocated to account for additional delays that could occur during longer dwellings). Therefore, bus stop capacity is equal to the product of the number of buses that can be served by a single loading area, the number of effective loading areas and a traffic blockage adjustment factor, during a given period of time; most commonly within an hour of time. This relationship can be expressed as following:

$$B = \frac{3600(g/C)}{t_c + t_d(g/C) + t_{om}} N_{el} f_{tb} \quad (1)$$

Where:

B	= Capacity of a bus stop (bus/h)
g/C	= Green time ratio (ratio of effective green time of the movement carrying the buses to the cycle time of a signalized intersection adjacent to the bus stop)
t_c	= Clearance time (s) which is the sum of the start-up time between buses and re-entry delay per bus
t_d	= Average dwell time (s)
t_{om}	= Operating margin on dwell time, determined by assuming a normal distribution of dwell times, coefficient of variation of dwell times (C_v), and a standard normal variable corresponding to the design failure rate (Z) (s), and estimated by $ZC_v t_d$
N_{el}	= Number of effective loading areas
f_{tb}	= Traffic blockage adjustment factor

According to Equation 1, the green time ratio is included as a factor to reflect that the buses cannot access any loading area immediately upstream or downstream of a signalized intersection during red time periods. If there is no immediate signalized intersection, then the ratio g/C becomes 1, and the effect of red time periods is no longer considered. Number of effective loading areas is a substitution that the TCQSM methodology uses to reflect the reduction in capacity that occurs due to interference between buses. A bus stop having multiple loading areas has a greater chance of underutilizing loading areas due to buses blocking each other. Hence, it substitutes the actual number of loading areas with an effective number of loading areas where N_{el} = number of actual loading areas multiplied by bus-bus interference factor. Traffic blockage adjustment factor (f_{tb}), represents the reduction in capacity that could occur due to general traffic requiring some capacity of the lane used by the buses right at the bus stop. Depending on the traffic condition and bus stop location, traffic blockage adjustment factor can take a value between 0 and 1. Refer to (Hisham et al., 2018) for detailed description on capacity reduction factors.

Clearance time is defined as the addition of two components; namely (i) time taken by a bus to start up and travel its own length and time taken by the next bus to pull in (t_{su}) and (ii) the time taken by the first bus waiting for a gap in the adjacent lane to merge into the traffic (re-entry delay-t_{re}). t_{su} is a fixed time and corresponds to the mechanical properties of the bus, while t_{re} can vary depending on the stop location. When a bus stop is located away from an upstream traffic signal and outside the influence of a downstream traffic signal, traffic is assumed to arrive randomly towards the bus stop (Case 1). Then buses would wait for a suitable gap to enter into the traffic lane. In this case, the re-entry delay for the bus is the time taken for the bus to find an acceptable gap. When a traffic signal is present, the signal would release the traffic as platoons. The remaining traffic will queue upstream of the signal until the signal turns green. When a bus stop is located upstream of the traffic signal, the built up queue may block the exiting bus (Case 2). In such a situation, firstly the buses will have to wait for the queue to clear, and secondly wait for a suitable gap to merge into the traffic lane. Therefore, re-entry delay for Case 2 is the addition of the time taken by the bus waiting for the queue to clear and the time taken by the bus waiting for an acceptable gap.

The method to estimate re-entry delay (t_{re}) produces an estimate of maximum average delay that could occur in waiting to enter the adjacent traffic lane. However, in jurisdictions such as Australian states, a YTB law prevails such that buses effectively force entry when they are ready to depart the bus stop after dwelling, no matter when this occurs during the signal cycle. This results in two effects that are not reflected in the theory presented above. First, the re-entry delay to buses can be reduced significantly. Second, the forced re-entry of buses into the adjacent lane can take away some of the available capacity to traffic in the adjacent general traffic lane. In order to achieve the study aim, it is necessary to develop a better understanding of these two effects and their associated impact on the relationship between capacity of the bus stop (and therefore bus facility) and the adjacent lane general traffic capacity.

4. Microscopic Simulation of Vehicle Operation at a Bus Stop

Microscopic simulation can be used for situations where there is a need to represent real world situations and reproduce its behavior. To better understand this complex interaction between buses and adjacent lane general traffic, we developed a microscopic simulation model testbed of an off-line bus stop with one adjacent general traffic lane. In contrast to deterministic models, microscopic simulation modelling provides a visual representation of each scenario. Another key advantage of simulation is that it permits the user to test operation across a complete range of bus volumes and adjacent lane traffic volumes of the testbed. In most circumstances it would be infeasible to collect data across such a complete range at a field bus stop.

Even though there are many traffic microsimulation packages available, only a few model transit vehicles. AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-urban networks) is one of them. It consists of a collection of dynamic modelling tools. Aimsun also has sub-models such as car-following, lane changing, gap-acceptance and overtaking models to effectively represent traffic conditions. The simulation software has been applied extensively in commercial projects across a wide range of environments, where its capability of microsimulation is tested and verified (TSS, 2018).

4.1. Car-Following and Lane Changing Models

Aimsun uses its car-following and lane changing models to realistically match the flow of individual vehicles in the network. Both of these models evolve from the Gipps model (Gipps, 1981, Gipps, 1986). Car-following behavior describes how a given pair of vehicles interact with each other. In Aimsun the car-following model ensures that a safe following distance is maintained, and the driver's behavior is adapted to always maintain it. The model assumes that the following vehicle chooses its speed such that it can maintain a safe distance behind a lead vehicle by accelerating and decelerating whenever needed.

Decision making for lane changing in Aimsun occurs in terms of *possibility*, *desirability* and *necessity*. These are governed by the turning possibility, the distance to the next turning position and local traffic conditions. For a roadway with a single lane, this model is used when buses need to re-enter the traffic. For instance, when a bus tries to re-enter into the adjacent traffic lane from the bus stop, Aimsun recognizes it as a *necessity* to change lanes because the distance between the current position and the next turn is very low. Lane changing during a necessity is different from lane changing when it is possible or desirable, because vehicles are being forced to reach their desired lane when there is a necessity. During this immediate action of the lane changing bus, vehicles in the adjacent lane would modify their behavior in order to allow a gap large enough for the bus to merge into and make the lane changing possible (Barceló and Casas, 2005). This is reflective of bus operation with YTB rule, where buses would re-enter the traffic with no delays while vehicles on the traffic lane will slow down or even come to a complete stop while giving way to the exiting bus.

4.2. Public Transport Model

In Aimsun the required inputs for a public transport are, route of each line, stop location, departure frequency (fixed or stochastic) and dwell time (fixed or stochastic) for each stop.

4.3. Microscopic Simulation Model Development

The microscopic simulation model developed in this research provides a realistic representation and reproduction of a testbed. The basic data required for the model development include; network geometry, characteristics of vehicles, driver characteristics and driver behavior, travel demand, traffic control systems and traffic flow models (car-following and lane changing).

In this study, the Case 1 testbed comprises of a single general traffic lane and a linear off-line bus stop, which reflects the layout demonstrated in Figure 1. A public transport plan is included with several public transport lines with preassigned dwell times and standard deviations. Arrival pattern of the buses were assumed to follow a normal distribution. Preassigned values such as bus dwell time and bus headway were adjusted according to suit the simulation scenario.

In order to monitor the behavior of buses detectors were placed along the testbed section. The model mainly considers stopping buses at bus stops, vehicles travelling in the adjacent lane, and buses trying to re-enter into the adjacent lane. The aim is to reproduce the behavior of the system under various combinations of bus flows and adjacent lane traffic to establish the relationship between bus stop capacity and adjacent lane capacity.

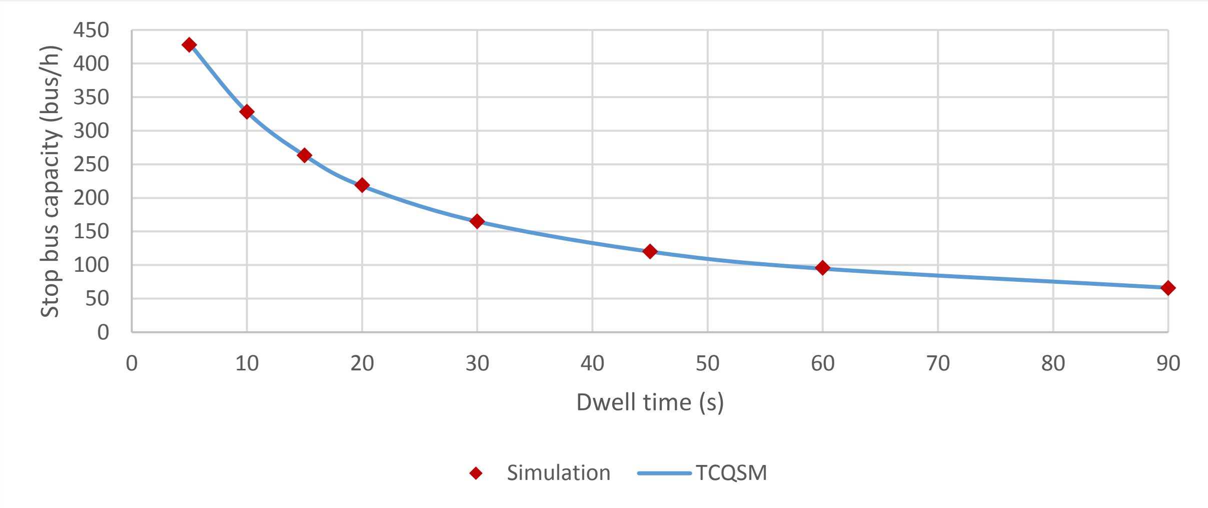
Following are the parameters used for the simulation experiments. Buses were assumed to be standard 12m (40ft) rigid. Drivers' reaction time, reaction time at a stop, and reaction time at a traffic signal are some of the parameters. They govern the traffic flow models; car following and lane changing models, which affect the performance of the entire network. A simulation step of 0.20s was used in order to ensure that the drivers' behavior is accurately modelled. Driver reaction times were set the same for all drivers including bus drivers, which was assigned to be 1.20s at a bus stop and 1.60s at a traffic signal. Because Aimsun is a stochastic simulation model, results differ with each replication. Each replication was carried out for one hour and ten replications were performed to estimate an average for a reliable result.

4.4. Model Verification

We define the limit state bus capacity of a bus stop to be the maximum achievable outflow of buses (Widanapathiranage et al., 2015). Using Equation 1, limit state bus capacity was estimated using the TCQSM model but with no operating margin. The number of effective loading areas (N_{el}) suggested by the TCQSM for an off-line bus stop with two loading areas equal to 1.85 was used.

The bus capacity achievable under the simulation model was found by modelling conditions of continuous upstream bus queuing with no adjacent lane general traffic. This was attained by creating a saturated state such that inflow to the bus stop exceeded the outflow of the bus stop. A virtual detector was placed downstream of the bus stop to measure the exiting bus flow rate, being the limit state capacity. A range of conditions of dwell times were modelled. In all cases, all of the buses stop at the bus stop using one of the two loading areas such that there were no through buses in the passing lane.

Figure 2: Bus capacity of testbed bus stop versus dwell time (Case 1 Away from Influence of Signalized Intersection)



Dwell times ranging from 5s to 90s were simulated. A 5s dwell time represents the case where a bus arrives at the bus stop, opens and then closes doors, and departs almost immediately. This was simulated to attain the highest capacity achievable at the bus stop. Average dwell times range from 10s to 60s for a bus stop located at an arterial road (Kittelson and Associates, 2013). However, to obtain a lower range of capacity, a dwell time of 90s was also simulated. Figure 2 illustrates maximum capacities obtained by varying dwell times.

10 replications for each dwell time were simulated. The average of the simulated values were cross validated with the values obtained from the TCQSM theoretical model. The models were compared by finding the Root Mean Square Error (RMSE). RMSE was found to be 0.91 (R^2=0.84). This shows that the simulation model fits well with Equation (1). Therefore, comparisons could then be made between the TCQSM model and the simulation model in terms of their estimation of bus stop capacities and associated re-entry delay components under various scenarios.

5. TCQSM Theory and Microscopic Simulation Model Implementation

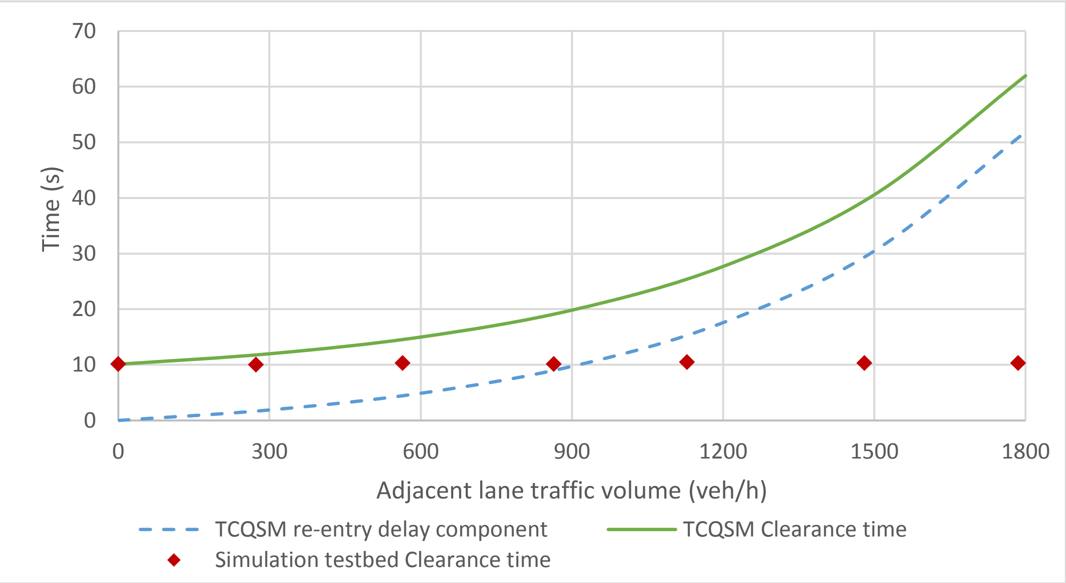
5.1. Case 1: Bus stop away from signalized intersection

The limit state bus capacity of a bus stop was determined using two methods; the TCQSM method of Equation 1, and Aimsun simulation model testbed developed in this study. A bus stop away from the influence of any signalized intersection is considered in this case. General traffic shares the same lane with buses, is assumed to arrive randomly upstream of the bus stop and pass the bus stop in the adjacent general traffic lane. The traffic volume was varied from 0 veh/h to 1,800 veh/h, and for each input traffic volume, maximum achievable outflow of buses and outflow of general traffic were measured using the virtual detector placed downstream of the bus stop. The maximum achievable outflows reflect the limit state capacities of buses and general traffic respectively.

According to TCQSM theory, buses arrive at the bus stop, dwell in the loading area to serve passengers, and re-enter the adjacent general traffic lane from the bus stop. If there is a sufficient gap the bus would re-enter into the traffic lane immediately, otherwise the bus would wait for an acceptable gap in the traffic lane. As the adjacent lane general traffic volume is increased, longer re-entry delays are expected at the bus stop accordingly. An average dwell time of 20s was used throughout this study to reflect a typical bus stop operation and with no operating margin (Widanapathiranage et al., 2015). Startup component of clearance time was assigned as 10s for a standard bus (Levinson, 1997). Re-entry delay was estimated using the TCQSM theory and subsequently bus stop capacity was calculated using Equation 1.

Simulations were conducted using the testbed under the YTB rule at the bus stop. Clearance time was then measured within the simulation model. Figure 3 shows the clearance times estimated by the TCQSM theory and the simulation testbed for increasing adjacent lane volumes.

Figure 3: Delay components of clearance time versus adjacent lane traffic volume for a bus stop away from the bus stop

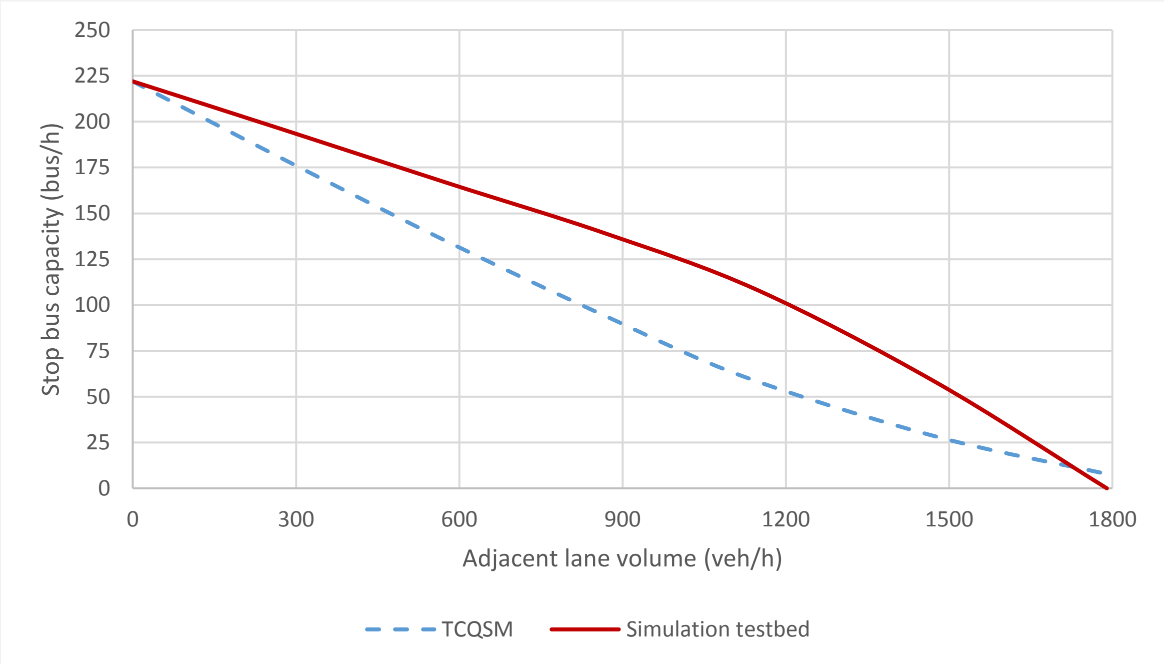


Clearance time comprises of two components; the time for the bus to start up and clear its own length plus the time taken to re-enter to the adjacent lane. In this study we assumed that the buses have the same start up time. When there is no signalized intersection nearby as in Case 1, re-entry delay is the time taken for gap acceptance. It is apparent from Figure 3 that under the TCQSM theory, with the increase in the adjacent lane traffic volume, buses have to wait longer in the bus stop to re-enter due to shorter headways in the traffic. However, the simulation testbed shows that a steady clearance time can be maintained without appreciable re-entry delay can be facilitated under the YTB rule.

Figure 4 illustrates bus stop limit state bus capacity measured on the simulation testbed as well as that estimated using the TCQSM methodology, as adjacent lane general traffic volume varies. Buses were simulated with 10s headway, which corresponds to an inflow of 360bus/h. With no adjacent lane traffic, it was observed that outflow was similar to the inflow.

As represented by the red curve, the simulation testbed gives the same bus capacity as the TCQSM methodology when no adjacent lane traffic is present and when the bus inflow exceeds the limit state capacity. It is evident that, according to the TCQSM methodology, capacity reduces almost linearly until the adjacent lane general traffic volume reaches 900veh/h. Subsequently, the values drop in a concave manner. This can be explained by the rapid increase in the re-entry delay which can be seen in Figure 3, since the bus stop capacity and the clearance time are inversely proportional to each other It is important to note that in Figure 4 the TCQSM methodology produces a one-way effect; the adjacent lane traffic volume (X axis) affects the stop bus capacity (Y axis), however the stop bus capacity does not affect the adjacent lane traffic capacity, as adjacent lane traffic volume is purely an input to the deterministic model.

Figure 4: Bus stop bus capacity versus adjacent lane traffic volume (Case 1 away from influence of any nearby signalized intersection)



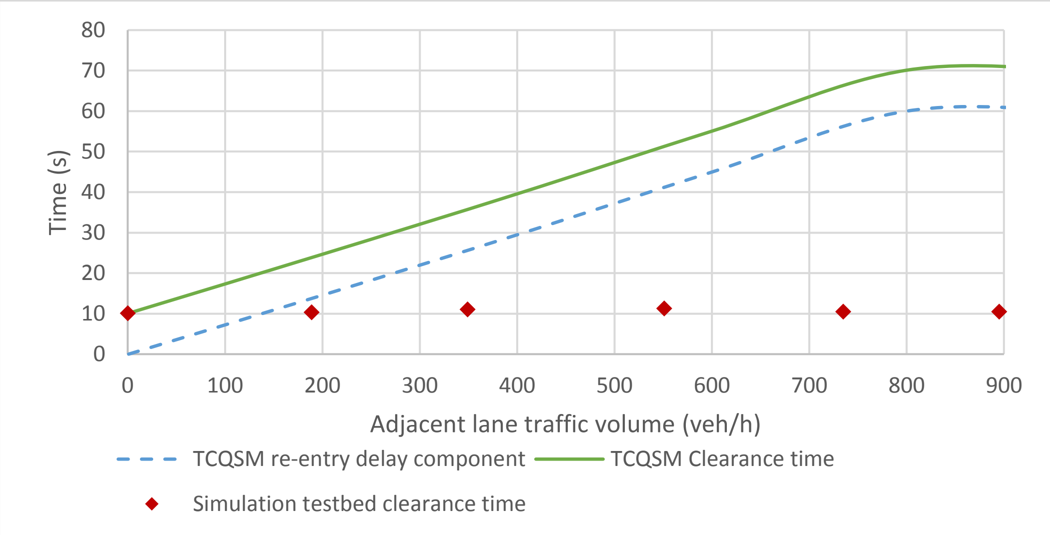
As adjacent lane traffic volume increases, the simulation testbed gives higher bus capacities than the TCQSM model, because general traffic yields to re-entering buses at the bus stop. The process is more efficient for buses. As the adjacent lane general traffic volume reaches pure saturation under the car following logic (see Y axis at 1,800 veh/h), bus stop capacity necessarily reaches zero. This occurs because, regardless of the YTB rule, there is insufficient time-space to accommodate any buses in the adjacent lane approaching the bus stop and hence no arrivals at the bus stop are possible. It is important to note that in Figure 4, unlike the TCQSM methodology, the simulation testbed produces a two-way effect; the adjacent lane traffic volume (X axis) affects the stop bus capacity (Y axis), while any particular measured stop bus capacity is also reflective of the maximum volume of adjacent lane traffic, in other words its limit state capacity that can support that stop limit state bus capacity under the YTB rule.

Any location on the red curve that was calibrated using the simulation testbed is therefore reflective of both stop bus capacity and an adjacent lane general traffic capacity, which is necessarily a consequence of the YTB rule. Whereas any location on the blue dashed curve is only reflective of a stop bus capacity under an adjacent lane traffic volume that has absolute priority over bus re-entry.

5.2. Case 2: Bus stop upstream of the signalized intersection

A bus stop located upstream of a signalized intersection is considered in this section. General traffic is assumed to arrive randomly at the bus stop and pass the bus stop when the signal is green. When the signal turns red, traffic will queue upstream of the intersection and past the bus stop. Depending on the traffic volume, durations of the green time and of the signal cycle time, and the distance between the signalized intersection and the bus stop, queues may block the bus stop at certain times. Once the signal turns green, it would release the traffic as a platoon. According to the TCQSM methodology, if the queue does not block the bus stop, then the bus will re-enter into the adjacent traffic lane upon an acceptable gap. If the queue blocks the bus stop, then the re-entering bus would wait until the queue is cleared and then find a suitable gap to re-enter into the adjacent traffic lane. Unlike the previous case, re-entry delay has an additional component which is defined as queue service delay (Kittelson and Associates, 2013). Simulations were conducted using the testbed under the YTB rule at the bus stop and clearance time was then measured within the simulation model

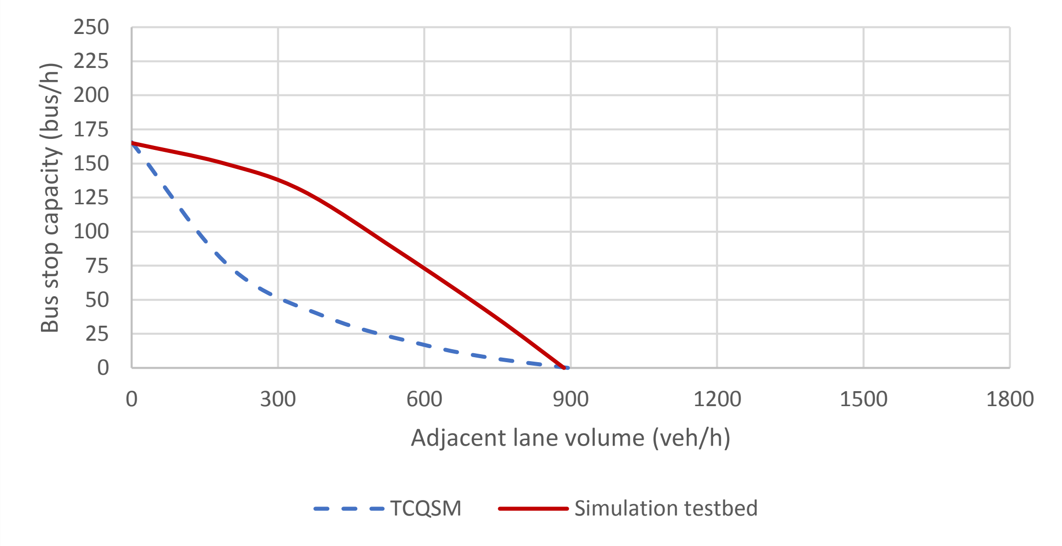
Figure 5: Delay components of clearance time versus adjacent lane volume for a bus stop upstream of a signalized intersection



It is important to note that, with the increase in the adjacent lane volume, queue service delay increases rapidly. This causes due to the queue forming upstream of the signalized intersection during the red time of the signal cycle. The maximum re-entry delay that could occur during one signal cycle does not exceed the green time because the bus stop is located adjacent to a signalized intersection, and once the signal turns green buses can use up green time to exit the bus stop. Therefore, the maximum re-entry delay that could be expected, is equal to the green time phase. The rapid increase in the re-entry is reflective on the stop bus capacity.

Figure 6 illustrates the limit state stop bus capacities obtained by both methods for a dwell time of 20s, signal cycle time of 120s and green time of 60s. Buses were simulated with 10s headways to obtain an inflow of 360bus/h.

Figure 6: Bus stop bus capacity versus adjacent lane traffic volume (Case 2 bus stop near side of signalized intersection)



A significant drop in limit state bus capacity can be observed in the TCQSM curve due to added delays buses will experience because of the red time of the traffic signal. It is noteworthy that, even though the signalized intersection processes traffic for only 60s or half of the time, the limit state bus capacity does not entirely become half of that achieved in Case 1. This is because some of the dwelling occurs during the red time on the signalized intersection, which contributes towards the capacity of the bus stop. As the adjacent lane general traffic volume increases, bus capacity decreases substantially, due to queues forming upstream of the signalized intersection. As with case 1, in Figure 4 the TCQSM methodology produces a one-way effect; the adjacent lane traffic volume (X axis) affects the bus stop capacity (Y axis), however the bus stop capacity does not affect the adjacent lane traffic volume, which is entirely an input to the deterministic model. This again implies that adjacent lane traffic volume is not a reflection of adjacent lane general traffic capacity.

The simulation testbed yielded substantially higher stop bus capacity than the TCQSM model. The red curve shows that, when the adjacent lane general traffic volume is more than 200veh/h the stop bus capacity achievable by the simulation can be twice or more than the capacity that is predicted by the TCQSM model due to YTB rule. As with case 1, as the adjacent lane volume reaches saturation under the car following logic, stop bus capacity necessarily reaches zero because there is insufficient time-space to accommodate any buses in the adjacent lane approaching the bus stop. Again, in Figure 4, unlike the TCQSM methodology, the simulation testbed produces a two-way effect; the adjacent lane traffic volume (X axis) affects the bus stop capacity (Y axis), while any particular measured bus stop capacity is also reflective of the maximum volume, in other words its limit state capacity, of adjacent lane traffic.

6. Comparison between Normal Bus Re-entry and YTB Rule Conditions

The principal difference between the TCQSM methodology and the simulation testbed is that, the former gives absolute priority towards adjacent lane general traffic, while the latter operates with YTB rule at the bus stop. Table 1 therefore compares the stop limit state bus capacity between normal bus re-entry conditions and conditions with the YTB rule under Cases 1 and 2.

Table 1: Stop limit state bus capacity comparison between normal bus re-entry conditions and YTB rule

Adjacent lane traffic volume (veh/h)	Stop Bus Capacity (bus/h)					
	Case 1: Away from influence of nearby signalized intersection			Case 2: Downstream signalized intersection		
	Normal Conditions (TCQSM)	Testbed (YTB Rule)	Improvement	Normal Conditions (TCQSM)	Testbed (YTB Rule)	Improvement
0	222	222	0%	167	167	0%
300	180	196	9%	50	140	180%
600	137	166	22%	17	70	311%
900	95	140	48%	0	0	Nil
1200	61	95	57%	N/A	N/A	N/A
1500	28	51	82%	N/A	N/A	N/A
1800	8	0	Nil	N/A	N/A	N/A

Table 1 and Figure 3 reveal that both the capacities with normal conditions and the simulation with YTB rule produce similar limit state bus capacities for a bus stop with no downstream signalized intersection, when there is no general traffic present in the adjacent lane. As the traffic increases in the adjacent lane, bus stop capacity is expected to reduce because some of the lane capacity would be accommodated by the general traffic. This is clear from the table above. When the adjacent lane volume goes up to 300veh/h, TCQSM bus capacity drops by 19% whereas the simulation capacity with YTB rule, drops by only 12%. Similarly, the capacity reduction estimated with YTB rule is less than the capacity estimated with normal bus re-entry, at all times.

When a signalized intersection located downstream of the bus stop, bus stop capacities drop significantly, because buses only process through the signalized intersection during the green time. For under saturated conditions, for a given green time and cycle time, as more adjacent lane traffic is discharged through the signalized intersection, more queue service time is required, meaning that less green time is available for gap acceptance by re-entering buses when there is no YTB rule. This explains the rapid drop in capacity with normal bus re-entry. However, the simulation testbed, with YTB rule, shows that when the adjacent lane volume reaches 150veh/h, more than 100% of the TCQSM capacity can be achieved because re-entry delay is practically eliminated. Therefore, according to the presented cases, it can be said that, by incorporating YTB rules more stop bus capacities can be achieved for an offline on-street bus stop.

7. Discussion

TCQSM methodology does not provide a clear understanding for the case where the adjacent lane volume reaches the saturation flow rate. It is assumed that even though the high traffic volume can reduce the capacity due to the traffic blockage, the bus stop can still have a considerable amount of buses approaching towards the bus stop which will eventually return a bus stop capacity. In reality, this will not be case. Once a lane reaches its capacity, the lane will no longer accommodate buses. This is reflective in the simulation model by returning zero capacity, as no buses will arrive at the bus stop. Furthermore, the higher bus stop capacity achieved from the simulation test bed is reflective of the YTB laws at the bus stop. This means, the simulation model can accurately model YTB rules, which cannot be demonstrated by theoretical methodologies. One more advantage of the simulation testbed is that, it provides a two-way relationship between the bus stop capacity and the adjacent lane traffic volume. Unlike the TCQSM approach this relationship provides an understanding about the maximum volume of the adjacent lane traffic that can support the bus stop under YTB rule, for a measured bus stop capacity.

8. Conclusions

Bus capacities of on-street off-line bus stops can be significantly increased by reducing re-entry delay. Re-entry delay can be reduced considerably by YTB laws where buses are given priority in the vicinity of a bus stop.

The present TCQSM model predicts bus stop capacities for high traffic adjacent lane volumes, however, the vice versa cannot be achieved. Since the predicted simulation testbed provides a two-way relationship, it can be used to determine the maximum adjacent lane traffic volume that could support a measured bus stop capacity with YTB law. Furthermore, TCQSM does not provide a clear understanding about bus stop capacities under saturated lane conditions. However, the simulation model can be adjusted accordingly to determine bus stop capacities for various traffic conditions, including saturated conditions.

Implications of “Mandatory give way (MGW)” zones in the bus stop could significantly change the interacting mechanism among buses and arriving traffic in the adjacent lane. When a bus is about to exit the bus stop, right indication would advise the arriving traffic to give-way to the exiting bus either by slowing down or coming to a complete stop. Once the bus merges into the curb lane without obstruction, general traffic can continue to travel. Advantage of MGW is that it can be implemented in a wide range road conditions without having to dedicate bus only lanes. Therefore, existing infrastructure can be utilized.

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