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Capacity-based feasibility boundaries for shared priority infrastructure for minibus taxis at signalised intersections

JP Mwenda, C Venter

JOHN-PAUL MWENDA (Pr Eng) is a distinguished professional transport engineer at AECOM, holding a master's degree with distinction from the University of Pretoria. With over a decade of industry experience, he has contributed to roadway design and comprehensive transportation studies on projects in the SADC region, USA and Canada. His pioneering research on optimising public transport operations has garnered significant attention from road authorities across Southern Africa.

Contact details:
Department of Civil Engineering
University of Pretoria
Pretoria 0002
South Africa
mwendajohnpaul@gmail.com

CHRISTO VENTER (Pr Eng) is a Professor of Transportation Engineering in the Department of Civil Engineering at the University of Pretoria. His teaching and research activities focus on public transport, transport policy and planning, travel demand modelling, and social aspects of mobility.

Contact details:
Centre for Transport Development
Department of Civil Engineering
University of Pretoria
Pretoria 0002
South Africa
christo.venter@up.ac.za

The minibus taxi (MBT) is the most widely used mode of public transport in South Africa, accounting for over 66% of peak hour public transport trips. Unlike buses, which benefit from dedicated infrastructure such as bus rapid transit (BRT) lanes with priority transit signals at intersections, MBTs currently lack such priority infrastructure to enhance their efficiency. Efforts by South African road authorities to provide priority infrastructure for MBTs are hindered by the absence of technical guidance on planning, design, and feasibility. This study addresses this gap by developing an analytical method to determine feasible traffic volumes for shared queue bypass priority lanes at pre-timed signalised intersections. The basic problem is that any priority given to MBT vehicles likely reduces the capacity available to other vehicles, which could lead to performance losses. Taking account of this interaction between MBT and general traffic volumes and the reallocation of vehicles to different lanes, we define feasibility as the combination of volumes where capacity is not exceeded for either vehicle type while still offering potential delay savings for MBTs. We produce a set of graphs that can serve as an initial assessment of whether intersections with medium to high MBT volumes may qualify for priority treatment, considering only existing geometric and traffic characteristics. Additionally, the study provides guidance on expected storage lengths for these priority lanes. Overall, the findings indicate that shared queue bypass lanes are effective when medium taxi volumes (approximately 20 PCU/hr to 85 PCU/hr) are present, provided that turning traffic in the shared left-turn lane is not excessively high (between 50 PCU/hr and 640 PCU/hr, depending on green time). Noting that drivers may adapt to priority intersections in unknown ways, we recommend further studies on the traffic safety implications of priority treatments under real operating conditions.

Keywords: Minibus taxi, shared queue bypass lane, intersection, Highway Capacity Manual, paratransit, transit priority

INTRODUCTION

Traffic congestion remains a major mobility problem in South African cities, leading to reduced traffic speeds and increased journey times, fuel consumption, operating costs, and environmental pollution (Bull 2003). According to the 2022 INRIX Global Traffic Scorecard report by Pishue (2023), the average annual delays for drivers commuting in Cape Town, Johannesburg, and Pretoria are 80 hours, 61 hours, and 42 hours, respectively. To address congestion and equity issues, the Department of Transport (DoT) adopted the public transport strategy (DoT 2006) to guide investment and upgrading of public transport. Integrated Rapid Public Transport Networks, which include provision of BRT systems, was one of the strategies introduced. This system currently renders services to buses only by providing them with dedicated lanes and transit signal priority (TSP) at intersections in several South African cities, including Tshwane, Johannesburg, Cape Town, and Rustenburg.

McLachlan (2021) observes that over the past decade, the South African government

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has constructed world-class depots and facilities for BRT buses that today serve a fraction of the demand met by the MBT industry. The MBT mode holds significant strategic importance to the South African government (DoT 2017; GDoRT 2021). While municipalities have invested in constructing lay-bys and ranks (terminals) for MBTs, other infrastructure-related strategies have not been explored to improve the operations and travel times for this mode, which carries the bulk of public transport users. The lack of priority infrastructure for MBTs at intersections – where most delays occur (Sampson 2019) – causes many MBT drivers to engage in illegal behaviour to bypass long queues. This phenomenon was observed by De Beer and Venter (2021), who noted that MBT drivers in South Africa display driving behaviour that simulates priority access. This behaviour includes queue skipping and opposite lane driving, which create safety problems. Their study quantified the potential benefits of three types of priority infrastructure – (a) queue jumping lanes, (b) single lane pre-signal strategies, and (c) dedicated public transport lanes – and found that an economic case can be made for the selective introduction of such interventions.

The advisability of implementing priority infrastructure for MBTs in any given location depends on many factors, including traffic conditions and composition, geometric conditions, and road user behaviour. A key factor would be the proportion of MBTs in the traffic stream: if this proportion is too low, the time-saving benefits to MBT passengers might be offset by the additional delay imposed on other vehicles; if it is too high, the priority sections would become saturated and deliver limited benefits. The design of priority intersections would require detailed traffic studies and site-specific analysis or simulation. Even before that, it would be useful for authorities to identify, as a first-cut analysis, intersections that might be potential candidates for such treatments, based on basic traffic, geometric, and control variables, enabling more focused data collection and feasibility assessments. No planning and design guides currently exist to help South African road authorities with this process.

This paper aims to fill this gap by developing an analytical method to provide a high-level assessment of the feasibility of implementing a shared priority treatment at the planning stage, based solely on existing geometric and traffic characteristics. The paper focuses on one type of treatment, where a normal auxiliary left-turn lane is converted into a shared lane reserved for MBT vehicles and turning general traffic, without requiring significant geometric upgrades to the intersection. The analysis determines feasibility boundaries in terms of the proportion of MBT to general traffic that could result in acceptable volume to capacity (v/c) ratios (thus avoiding oversaturation of the approach) at various ratios of green time to total cycle length (g/C). Graphs showing the relationship between traffic volumes, v/c ratios, g/C ratios, and storage lengths are developed to assess the adequacy of the existing geometry for accommodating the priority treatment. The paper concludes with general considerations regarding the implementability of priority infrastructure under local conditions.

LITERATURE

Status of informal public transport in South Africa

Wilkinson *et al* (2012) define informal public transport, also known as paratransit, as demand-driven, unscheduled transport provided by small operators, typically using mini- to medium-sized buses that operate along quasi-fixed routes, which may frequently change. Today, paratransit accounts for between 50% and 98% of passenger trips in Sub-Saharan cities (Jennings & Behrens 2017).

Although the paratransit industry is not entirely regulated, it is the most widely used form of public transport in South Africa. In Johannesburg and Cape Town, MBTs account for 66% of all public transport trips (Van Ryneveld 2018). Paratransit vehicles, such as MBTs, typically operate with minimal government oversight or regulation, often resulting in poorly maintained vehicles, unsafe driving behaviour, and fierce competition among operators for routes and passengers. In many parts of the world, including South Africa, informal public transport is the only available option for many residents, providing motorised transport where none may exist and offering employment to poor or lower-skilled workers (Jennings & Behrens 2017).

In response, municipalities across the country have implemented various approaches to upgrade and support MBTs, including the provision of infrastructure such as ranks and lay-bys. However, other priority infrastructure strategies have rarely been explored to improve the efficiency of MBTs.

Design guidance of priority infrastructure at intersections

In South Africa, planning and design guidelines include high-level clauses that highlight the importance of considering MBT priority infrastructure. However, these guidelines currently lack detailed information on feasible intersection choices and specific design details for such infrastructure. For instance, the Gauteng Department of Roads and Transport recently updated the design guidelines for bus and MBT facilities on major provincial roads in Gauteng. Among the design considerations, designers are expected to provide supporting intersection analysis modelling with and without transit priority facilities, with results showing vehicle movement and general intersection operational impacts (GDoRT 2021). However, no further design information is available for these priority treatments to assist transport system designers or planners.

Similarly, the City of Johannesburg conducted a sustainability study (CoJ 2013a) where several new or improved infrastructure elements were identified for implementation in the city. Some of the recommendations from the study, without further detailed design information, included provision of public transport priority measures such as queue-jumping lanes and signal priority on mixed traffic sections at intersections. Additionally, where information (Chitauka & Vanderschuren 2014) for priority facilities is available, most pertains to buses and the design of other types of priority infrastructure for public transport, such as exclusive bus lanes.

International guidelines, where detailed designs for priority infrastructure are presented, show that the design of priority at intersections uses a combination of control technologies and intersection geometry. The National Association of City Transportation Officials (NACTO 2016) in the United States observes that geometry guides street users through intersections, working in tandem with signals to manage conflicts and establish priority among users. The guide also states that intersections can be organised by designating turn and through lanes, setting clear vehicle and walking paths through the intersection, and providing transit vehicles with a way to avoid general traffic queues and make use of signal priority treatment.

The Southern California Association of Governments (SCAG 2022) conducted a study on transit priority best practices as part of the research to provide guidelines for effective and sustainable transit options for the California region. The study grouped transit treatments into two main groups: design or infrastructure treatments, and operations and technology treatments. Infrastructure treatments are defined as facilities that make transit faster and more reliable. Typical examples of design treatments evaluated include bus lanes, far-side bus stops, bus bulb-outs, level boarding, facilitated left turns, floating bus islands, and bus-bicycle treatments. Operational and technology treatments are defined as strategies that complement design treatments to make service faster and more reliable. Examples include TSP, queue jump/bypass, bus stop balancing, and real-time information.

A study on the evaluation of transit signal priority strategies for small-medium cities by Ova and Smadi (2001) provides the fundamental design theory of transit treatments. The study focuses on TSP strategies, which include phase splitting, progression/coordination to favour priority vehicle movements, increasing the priority phase split, and queue jumps. The study indicates that passive priority strategies mainly consist of signal timing modifications favouring the transit vehicle but also include geometric or infrastructure enhancements.

Table 1 summarises guidelines for some of the design strategies or treatments suitable at intersections. It provides a summary of descriptions and applications of selected transit treatments related to shared types of priority lanes implemented or proposed at intersections. It is important to note that the priority infrastructure and guidelines outlined in the table are a starting point and do not apply as is to the MBT case in South Africa. This study utilised some of these design principles in developing and evaluating a shared type of priority infrastructure for MBTs at intersections.

Table 1 Summary of best practices related to transit treatment applications at intersections

Transit treatments	Description and application	Place or country of application
Queue bypass or transit approach lanes (Cesme *et al* 2014; SCAG 2022; CoJ 2013b; NACTO 2016)	**Description:** Queue bypass or transit approach lanes are bus-only lanes located on the nearside of left turn pocket. Geometrically, a queue bypass extends to the other end of a signalised intersection. It is a short lane used by public transport vehicles to bypass traffic queues at signalised intersections. It allows transit vehicles to bypass long queues that form at major cross streets. **Application:** It is used where a dedicated left turn lane is present, and traffic volumes are high. It is particularly applicable to intersection approaches with high through-lane queue delay and low left-turning volumes.	■ USA (Stockton St in San Francisco) ■ USA (Washington Street in Chicago; SBS86 street in New York City)
No car lanes (Mulley 2011)	**Description:** These are lanes used by buses, goods vehicles, and some other modes of transport, but cars are prevented from using the designated lane. **Application:** Specifically, they are used in cities with mixed traffic road networks whereby the priority lanes, if restricted only to public transport vehicles, would have spare capacity.	UK (Newcastle and Sunderland)
Shared transit lane (NACTO 2016)	**Description:** These are designed by converting a left-turning lane to accommodate moderate volume of left turn movements and through movements for transit vehicles. Alternatively, it is also designed by converting through movement for all vehicles to through movements for transit vehicles (transit approach lane). It does not necessarily use priority signals unless preferred to do so. **Application:** Can be used at locations where left-turning vehicles can typically clear through the intersection quickly	■ Spain (Barcelona) ■ USA (West Valley City, Utah)
Virtual transit lane (NACTO 2016)	**Description:** These lanes would permit left turns only when a transit vehicle is not present. When a transit vehicle approaches, left turns are prohibited. Transit signals are triggered to allow transit vehicles to pass through the intersection. **Application:** It is usually used at streets with moderate transit service frequency, often with cars operating in a mixed travel or shared turn lane. It is also used at intersections where left turns are subject to delays while yielding to pedestrians and bicyclists.	USA
Peak-only lanes (SCAG 2022)	**Description:** These are lanes reserved for transit at peak travel periods (such as the morning and evening commute) and are used for general traffic at other times of the day. **Application:** These may require repurposing the existing travel lane or parking lane, or providing additional right of way to support new construction.	USA (Wilshire Blvd, Los Angeles)
Far-side bus stops (SCAG 2022; De Beer & Venter 2021)	**Description:** These are located after an intersection, allowing the bus to travel through the intersection before stopping to load and unload customers. **Application:** They are beneficial in locations with long signal cycles or short green signal times.	■ USA (bus stops) ■ RSA (bus/MBT stops)

Intersection geometry and analysis

The literature on priority infrastructure (SCAG 2022; NACTO 2016; TRB 2010; CoJ 2013b) demonstrates that auxiliary lanes are extensively utilised to prioritise transit vehicles at intersections. In South Africa, COTO (2014) provides specifications for the design of auxiliary lanes, with the two most commonly used types being auxiliary through lanes and auxiliary turning lanes. Figure 1 illustrates the auxiliary lane at intersections.

The length of auxiliary lanes consists of three components: taper, deceleration length, and storage length. The taper and deceleration lengths are primarily determined by the approach speeds and other traffic characteristics. Estimating the storage length at intersections is crucial for predicting the overflow or blockage of auxiliary lanes (Yekhshatyan & Schnell 2008).

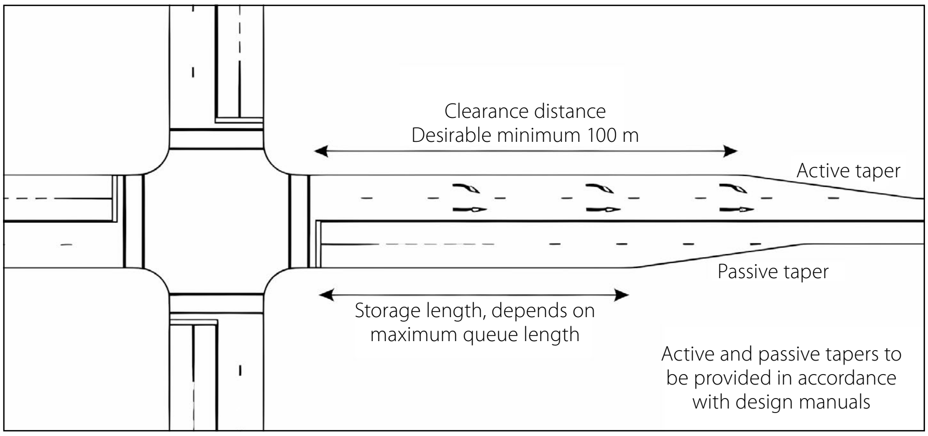

Figure 1 Auxiliary lanes at signalised intersection (Adapted from NDoT 2012)

Storage length

The storage lengths of auxiliary lanes at signalised intersections are determined by the maximum number of vehicles that will accumulate during a single signal cycle. In practice, these storage lengths range between 30 m and 60 m (NDoT 2012). At signalised intersections, the required storage length is determined through an intersection queuing analysis, which considers the signal cycle length, signal phasing arrangement, and the rate of arrivals and departures of turning vehicles (AASHTO 2018).

The storage length (L) is a function of the probability of occurrence of events and is typically based on 1.5 to 2 times the average number of vehicles that would store per cycle, derived from the design volume or traffic counts (AASHTO 2018). A value of 2 is applied when v/c ratios are close to 1, indicating variable and stochastic traffic queues, while AASHTO (2018) recommends a value of 1.5 for undersaturated conditions. Equation 1 is used to estimate the storage length for the 95th percentile queue under variable and stochastic conditions (Preston *et al* 2010).

$$L = \frac{\left[1-\left(\frac{g}{c}\right)\right]\left[DHV\right]\left[1+\left(\frac{\%heavy\ vehicles}{100}\right)\right]\left[d*2\right]}{(\#\text{ cycles/hour})(\#\text{ traffic lanes})} \qquad (1)$$

Where:

L	Storage length
$1 - g/c$	This defines the fraction of the signal cycle that is red for a particular movement. The formula assumes that vehicles only need to be stored during the red portion of the signal phase and that ALL vehicles that arrival on red clear the intersection on the following green phase
DHV	Design hourly volume for turning lane
$\left[1+\left(\frac{\%heavy\ vehicles}{100}\right)\right]$	Adjustment to hourly volume to account for heavy vehicles
d	Average storage length for a passenger vehicle (including gap)
Factor of 2	Randomness factor that converts the average storage length to a 95th percentile storage length
# cycles/hour	3600/C where C is the cycle length (in seconds)
# traffic lanes	Number of turning lanes (single or dual turning lanes)

Capacity analysis of signalised intersections

A capacity analysis is conducted to determine whether the transportation system can accommodate the expected traffic demand (COTO 2014). Pretorius *et al* (2004) note that various studies conducted in South Africa and Australia indicate that operational analysis of an intersection is complex and often yields invalid results. Consequently, they suggest employing simpler approaches, such as measuring volume/capacity ratios, instead of using complex models that may produce inaccurate outcomes.

Technical Methods for Highway Volume 2 (TMH16) recommends that capacity analysis of traffic signal-controlled intersections be undertaken using the method and model parameters provided in the Highway Capacity Manual (TRB 2010) (COTO 2014). This study adopts this approach to develop feasibility boundaries related to traffic volumes associated with a shared queue bypass priority lane.

Capacity evaluation using Highway Capacity Manual 2010

The Highway Capacity Manual (TRB 2010) outlines the methodology for analysing the capacity and level of service of roads in both urban and rural areas by defining the volume/capacity (v/c) ratio and delay of the analysed facilities (Nedevska *et al* 2016). To perform this analysis for a signalised intersection, geometric data, traffic data, and signal data are required. The HCM methodology follows the procedure indicated in Figure 2.

Key HCM formulae for capacity evaluation

The ratio of demand flow rate to capacity (v_i/c_i) represents the degree of saturation (TRB 2010). The demand flow rate (v_i) for lane group *i* is given by Equation 2.

$$v_i = \frac{V}{PHF} \qquad (2)$$

Where:

v =	Hourly traffic volumes in veh/hr
PHF =	Peak hour factor (typically between 0.85 and 0.95 for urban roads (Sampson 2019))

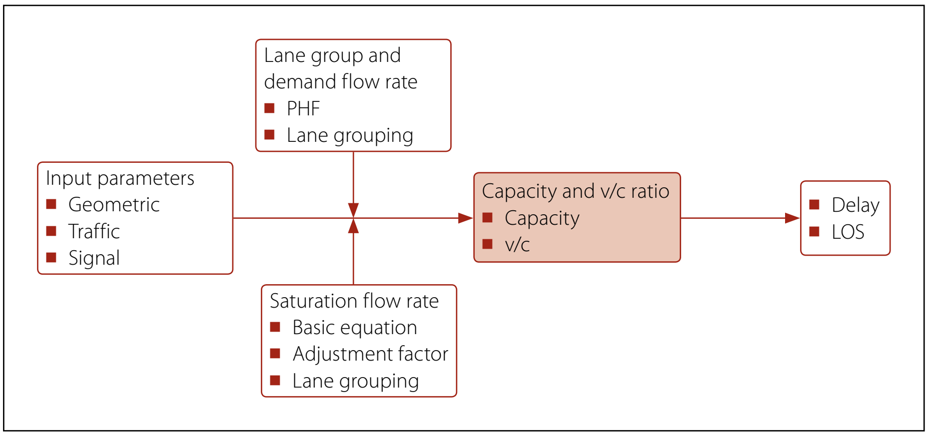

Figure 2 HCM procedure for signalised intersection (adapted from TRB 2010)

On the other hand, capacity (c_i) at signalised intersection is largely dependent on the concept of saturation flow and saturation flow rate and is given by Equation 3.

$$c_i = S_i \left(\frac{g_i}{C}\right) \qquad (3)$$

Where:

S_i = Saturation flow rate for lane group *i*

g_i/C = Effective green ratio for lane group i defined as ratio of green time (g) to cycle length (C)

Note: v_i/c_i ratios of equal to or less than 1 are said to be sustainable (undersaturated) whereas values of more than 1 are oversaturated.

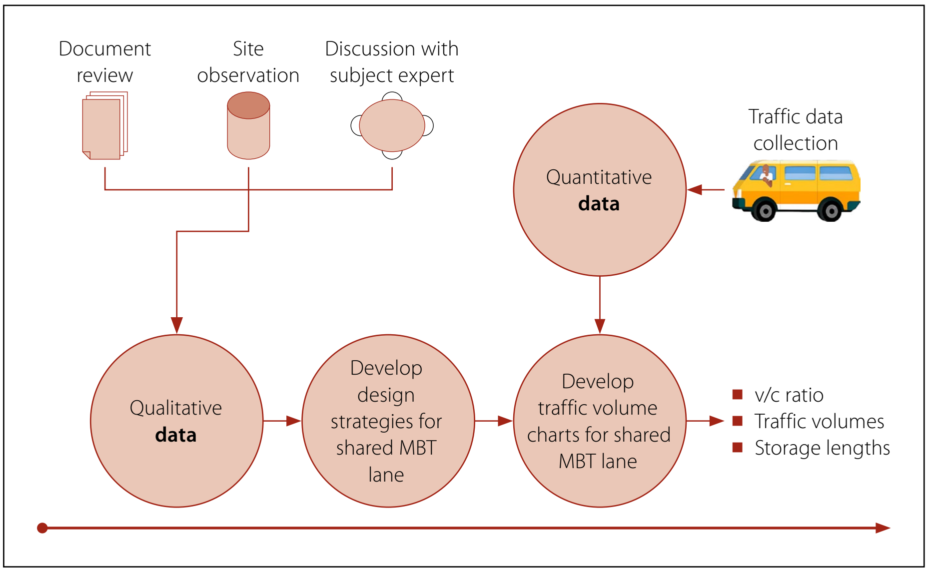

Figure 3 Summary of research methodology

METHODOLOGY

The methodology aimed to locate the study and its results within the context of typical operational conditions of South African urban roads. This required a comprehensive approach involving both qualitative and quantitative data collection stages. Subsequently, suitable design strategies for shared priority infrastructure were developed, along with an analytical model and graphical outputs (Figure 3).

Data collection

Data collection involved desktop document reviews, site observations, discussions, and traffic counts. Desktop reviews and qualitative observations of various intersections were conducted to determine design strategies for the shared queue bypass priority lane. In-depth discussions with industry experts focusing on traffic operations and safety were held before finalising the design strategies.

A desktop exercise was conducted to identify MBT corridors in the City of Tshwane that might include candidate intersections with high taxi volumes and suitable geometries, using area-wide traffic data and satellite images. Following site visits, four intersections were selected for an in-depth study of typical volumes and geometric considerations.[1] The purpose of these sites was not to create cases for detailed design, but rather to serve as examples of the types of issues that need to be addressed and to quantify typical operational parameters for the analysis.

At the four selected signalised intersections, classified traffic data was collected through 90 minute traffic counts using video cameras during the identified AM/PM peaks. All four intersections had major MBT traffic on the through movements and experienced undersaturated conditions during the peak periods. It is likely that oversaturated intersections would require significant upgrades to accommodate priority lanes, which is beyond the scope of this research. The results from the site visits also showed that through-MBT traffic volumes ranged from 3% to 7% of the total through-traffic volumes on all targeted approaches.

Development of design strategy

Literature has shown that priority infrastructure can be achieved in various ways (Table 1). This study focuses on a type of shared priority infrastructure known as shared queue bypass lanes. This involves utilising a standard auxiliary left-turn lane for general traffic, which is shared with priority (MBT) vehicles making a through movement during peak hours. Reasons for selecting this type of priority infrastructure include: (i) it can be implemented with minimal additional investment, depending on the existing geometry; (ii) it does not require additional signal phases that might be unfamiliar to drivers; and (iii) the concept of shared movements between priority (through) and general (turning) traffic is familiar in BRT lanes used in some South African systems (albeit for right-turning rather than left-turning traffic). Table 2 shows development of the geometric layout of a priority treatment intersection, where the dominant MBT movement that receives the priority is east-west. This is for reasons of clarity and parsimony only, as the method can be applied to any movement direction or simultaneously to all directions, since traffic flows are controlled by the green time allocated to each approach. To form the proposed geometric layout of a shared queue bypass lane, the following existing intersection conditions should be satisfied:

- The intersection should be four-legged with pre-timed signal control. However, priority treatment could also be applied to actuated signals with a different analytical approach due to varying g/C ratios throughout the day.
- The intersection should have single or multiple exclusive through (T) lanes.
- The intersection should have one auxiliary nearside lane on targeted approaches for left-turning (LT) traffic or single mixed left turn and through (LT/T) movement traffic. In the case of an auxiliary mixed lane (LT/T), during operation, general through traffic (T) would be reallocated to the remaining through lane, leaving the through-MBT and LT traffic to occupy the priority lane.
- If auxiliary nearside lanes are not already present, it must be possible to add them.
- Receiving lanes for the proposed shared queue bypass auxiliary lanes should be added on the farside, if not already present. The active tapers for receiving lanes of MBT traffic must be properly and adequately designed to reduce potential merging conflict with through traffic.

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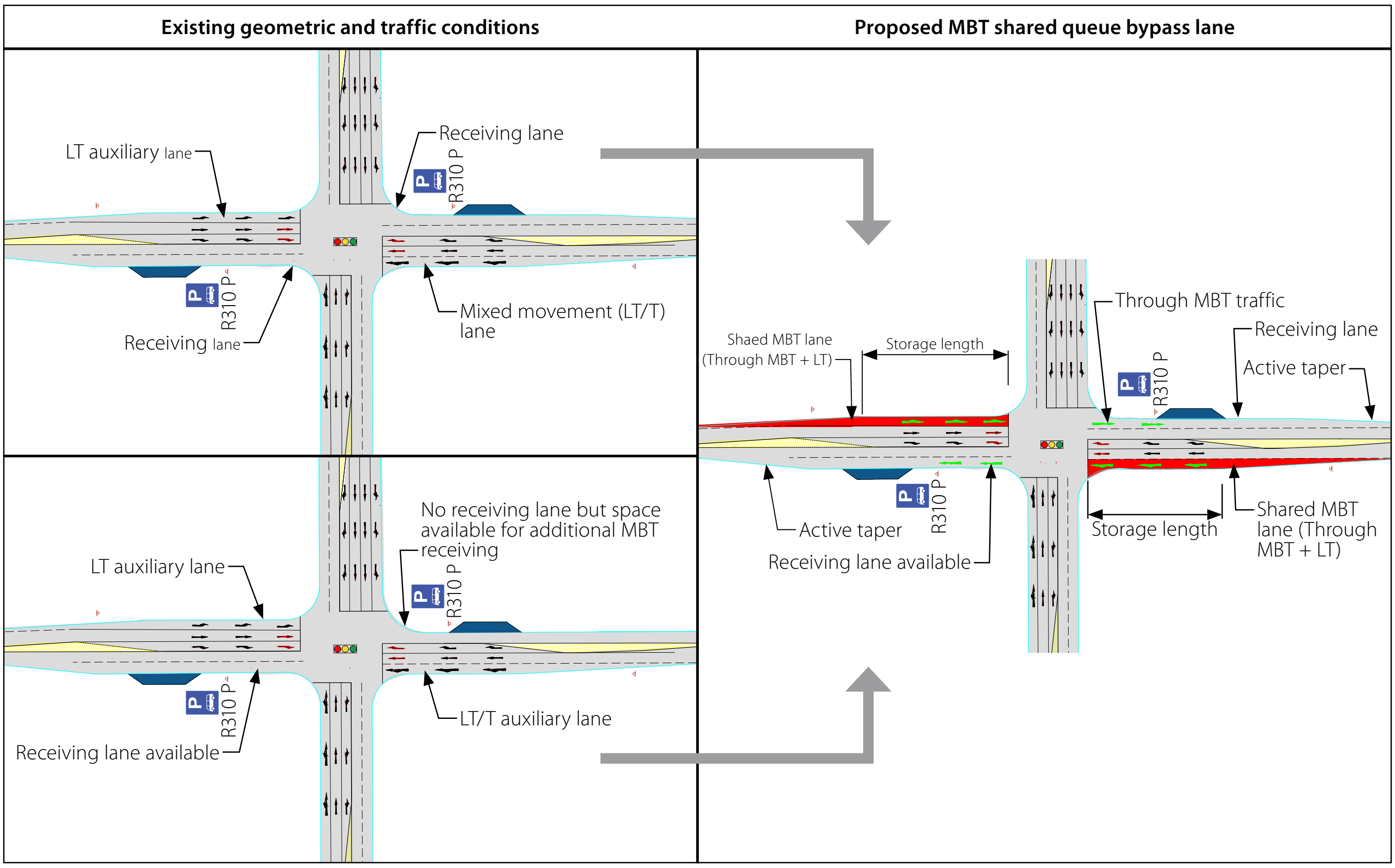
[1] The planning process to identify candidate intersections for MBT priority treatment falls outside the scope of this paper, but is described in more detail in a forthcoming publication.

Table 2 Development of a typical design strategy for shared queue bypass priority lanes on east-west approaches



- Farside MBT laybys must be present in both directions, to reduce the likelihood of taxis stopping in the intersection.[2]
- The intersection is assumed to have exclusive right turning (RT) lanes (although shared T/RT are also operationally feasible, this work does not apply to that case).
- The geometric conditions on the cross approaches (not receiving priority treatment) are not relevant. The variation in the g/C ratio captures the effect of cross traffic at the intersection for the non-targeted corridor.

Model assumptions

The analysis used Equation 3 to define lane capacities (c). Typical values for adjustment factors, traffic characteristics, and signalisation of urban roads in South Africa were used (Sampson 2019; Bester & Meyers 2007). Table 3 summarises the key adjustment factors and assumptions used to set up the HCM model for the analysis. These include base saturation flow (So), lane width, cycle length (C), and the turning radius of urban intersections. Similarly, adjustment factors were applied to the base saturation in Equation 4 to measure the saturation flow rate (S_i) to determine lane capacity (adapted from TRB 2010).

$$S_i = S_o N \, f_w \, f_{HV} \, f_a \qquad (4)$$

Additional assumptions

In addition to saturation flow rates, there are other variables that influence the performance of an intersection with priority MBT lanes. These variables include the volumes of general and MBT traffic, the balance of flows between the main and cross directions, and the traffic signal phasing and cycle length. To streamline the analysis and limit the number of variables under investigation, the following values were fixed during the analysis:

- **A 10% volume of the through-MBT traffic:** Traffic counts at the four sampled intersections indicated that through-MBT traffic on all approaches ranged from 3% to 7% of total through traffic (MBT+T) during peak hours. To account for the worst-case scenario, the volume of through-MBT traffic on each targeted approach was assumed to be 10% of the total through traffic (MBT+T). If actual MBT volumes are lower, the analysis accommodates future growth in MBT use before reaching the indicated performance boundaries. For corridors where MBT proportions exceed 10%, it is recommended that the additional MBT traffic volumes be considered as part of the general through traffic (T), as excess MBT vehicles will distribute themselves among all available through lanes once the shared lane becomes saturated.
- **Arrival pattern of general and MBT traffic:** The analysis assumed isolated intersections with random arriving traffic, i.e. without vehicle platooning.
- **Maximum lane v/c ratio of 1:** The volume/capacity ratio of 1 represents a level of service (LOS) of E (Othayoth & Rao 2019; COTO 2014), or capacity operations (when demand volume equals the capacity of the facility). This value was used as the upper limit for acceptable operations to capture the worst-case boundaries associated with real-world conditions. Although an upper limit of 0.85 is sometimes applied, COTO (2014) suggests that it can be relaxed to 1 for conditions which are not specified in the manual, during the peak 15-minute period.
- **Minimum lane v/c ratio of 0.6:** A v/c ratio of less than 0.6 is associated with

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[2] The practice of taxi vehicles illegally stopping within intersections to load/unload passengers is recognised as a problem that needs broader solutions including driver training and enforcement. This study does not address this problem in order to investigate the best-case operation of shared bypass lanes.

Table 3 Key assumptions and adjustment factors for the analysis

Key assumptions and adjustment factors	Values used
Base saturation flow (S_o) for LT traffic	1 900 passenger car unit (PCU)//hr/lane
Base saturation flow rate (S_o) for straight (MBT+T) traffic	2 000 PCU/hr/lane
Lane width	3.5 m
Number of lanes (N)	1 targeted lane (lane with highest v/c ratio)
Adjustment factor for lane width (f_w)	0.99
Adjustment factor for heavy vehicle (f_{HV})	0.98
Adjustment factor for area type (f_a)	0.9 for urban area
Intersection left turning radius	12 m
Peak hour factor (PHF)	0.85
Length of average passenger car including gap	6.0 m
Cycle length	80 seconds

the LOS of A or B which is a very good level of service (Othayoth & Rao 2019; COTO 2014). This study therefore ignored approach volumes that would result in v/c ratios below 0.6, as traffic conditions are good enough that there would be no incentive for MBTs to use priority lanes to bypass any queues that may form.

- **Reallocation of MBT traffic volumes:** The analysis assumed that the MBT through traffic would use the proposed shared queue bypass lane when LT traffic is less than the total through (MBT+T) traffic and the v/c ratio for the auxiliary lane is less than 1. Where the LT traffic volume is greater than T+MBT, the study assumed that MBT traffic would prefer to maintain the designated through lane(s) rather than use the auxiliary lane.

In order to derive feasibility boundaries across a range of operating conditions, sensitivity analyses were conducted across a range of values for the following three input variables:

- **g/C ratio:** The ratio of effective green to cycle length (g/C) influences the v/c ratios (Equations 1 and 3). Increases in green time allows more traffic to pass through the intersection per cycle. The variation in g/C ratio also captures the effect of cross traffic volumes on the non-targeted corridor. For instance, the higher the g/C ratio for the targeted corridor, the lower the cross-traffic volumes in the non-targeted and vice versa.
- **Left turning (LT) traffic:** The quantum of LT traffic is important since this traffic now has to share the lane with priority MBT vehicles during the same phase. If the combined volume in the shared lane (MBT+LT) exceeds the lane capacity, the v/c exceeds 1 and the combination is considered infeasible (although this was not tested, if the original lane was formed from a mixed (LT+T) auxiliary lane, the shared treatment might decrease the lane v/c if the additional MBT volume is less than the through (T) traffic it displaces).
- **Straight (MBT+T) traffic:** Straight general traffic is also impacted during traffic reallocation as MBTs shift from through lanes to priority lanes. The overall through traffic could also be impacted when the through (T) traffic in an auxiliary LT/T lane makes a shift to the remaining through lane.

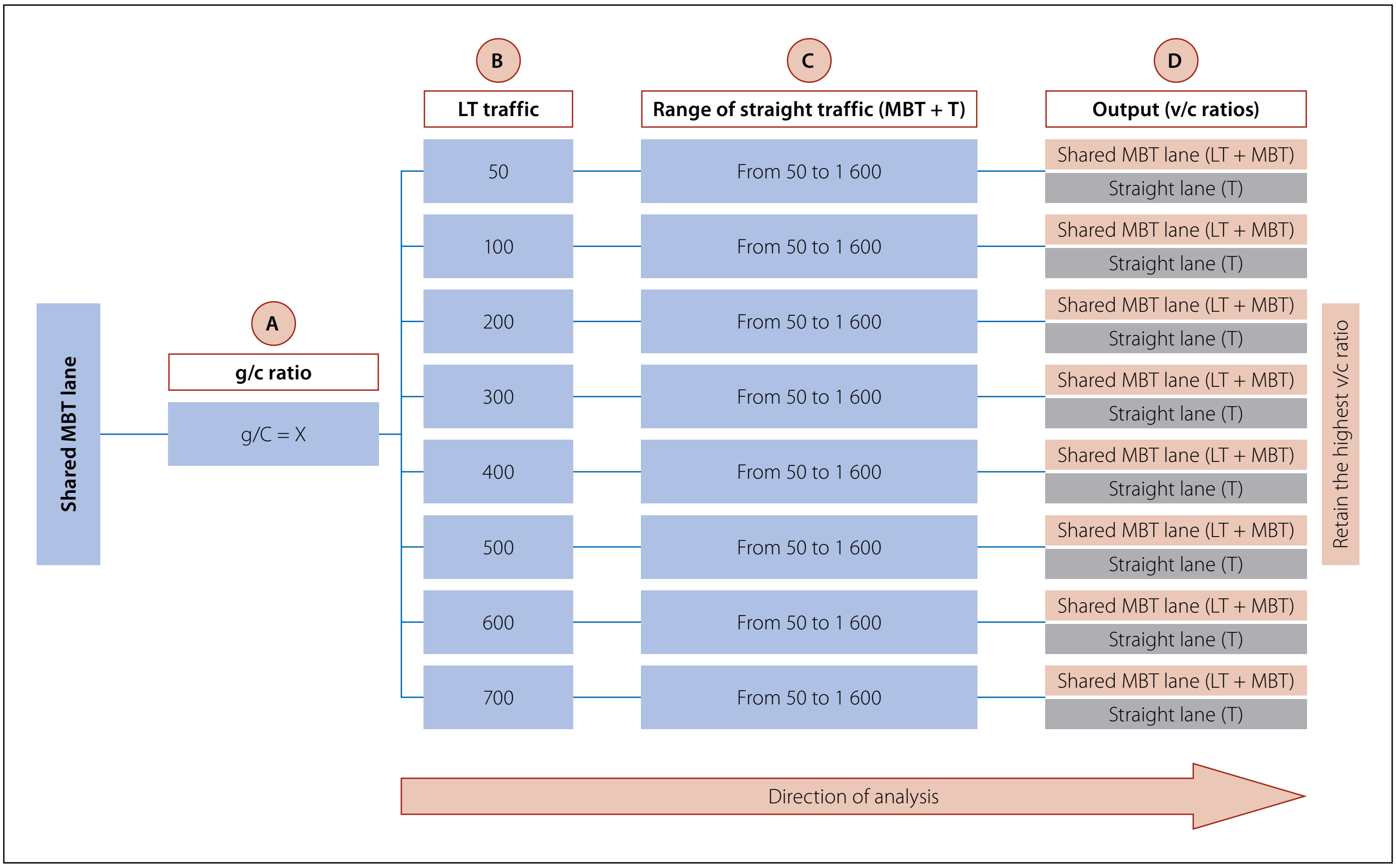

Figure 4 Graphical illustration of analysis procedure

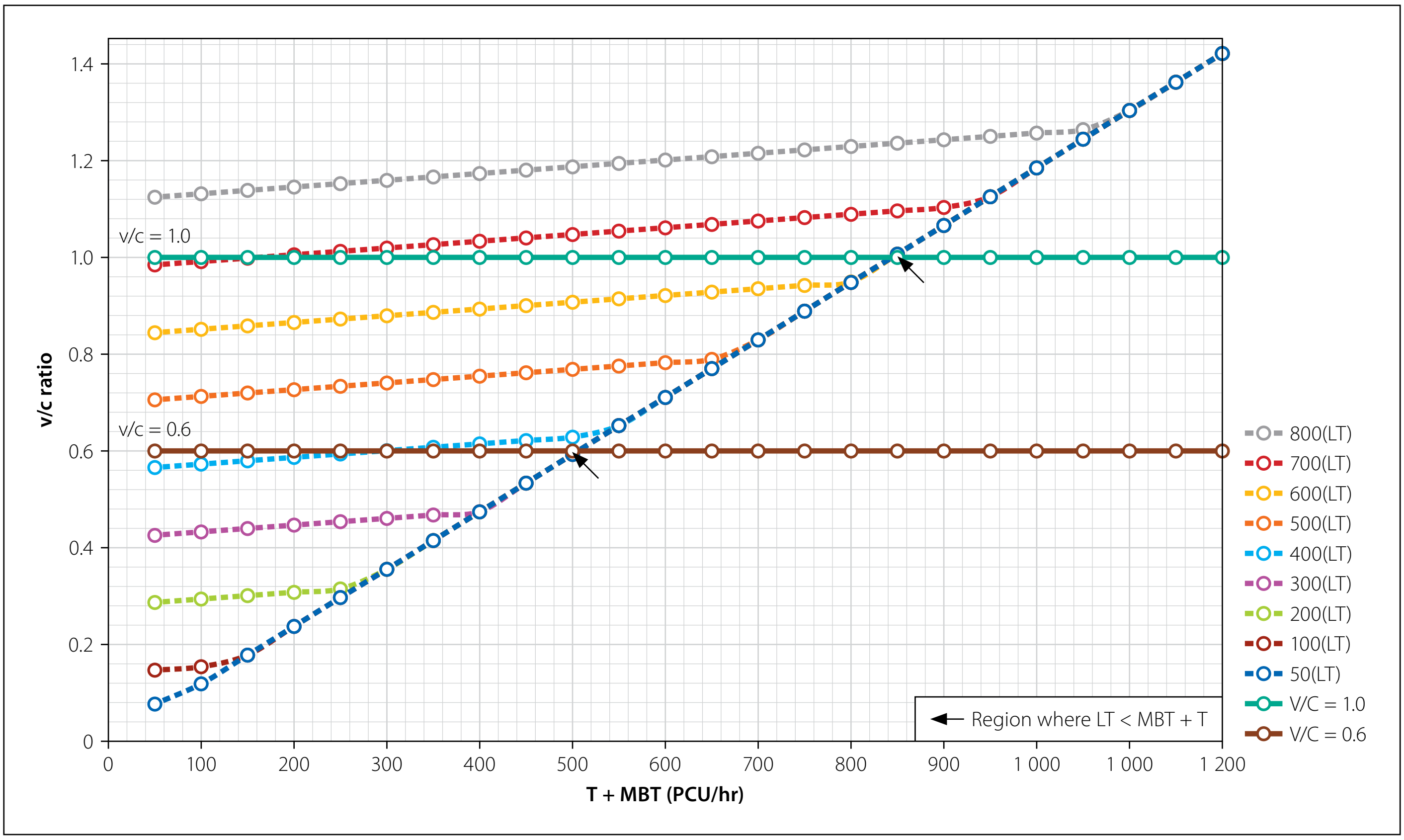

Figure 5 Relationship of v/c ratios and traffic volumes at g/C = 0.50

Analysis procedure

The analysis was conducted using the HCM procedure for evaluating the capacity of signalised intersections. The model was implemented in an Excel spreadsheet, allowing for the variation of three input variables: g/C ratio, LT volume, and MBT+T volume, while calculating the v/c ratio for all lanes. For each selected g/C value (ranging between 0.2 and 0.5), combinations of through MBT+T volumes (between 50 PCU/hr/lane and 1 600 PCU/hr/lane) and LT traffic volumes (between 50 PCU/hr and 800 PCU/hr) were used.

Since the resulting v/c ratios differed across the approach lanes of the targeted corridor, the model retained only the maximum (critical) v/c ratio. This ensured that only volume combinations resulting in all lanes being under the critical v/c ratio of 1 were considered feasible. Figure 4 illustrates the analytical process and output variables.

To calculate the storage length, Equation 1 was used for the 95th percentile queue for stochastic conditions. The equation considers g/C ratio, traffic volumes, traffic lanes and number of signal cycles per hour.

To facilitate interpretation, the results are presented graphically, depicting the maximum v/c ratios for each combination of the three input variables. The discussion of these results follows in the next section.

RESULTS

Determination of feasible ranges of traffic volumes

The results are presented using a series of graphs (Figures 5 to 8) that illustrate the relationship between traffic volumes (various combinations of LT and MBT+T) and v/c ratios at each constant g/C ratio. For instance, at g/C = 0.5 (Figure 5), with an LT volume of 500 PCU/hr, the v/c ratio gradually increases from 0.7 to 0.8 as the MBT+T volume increases from 50 PCU/hr to 650 PCU/hr. At this relatively high LT volume (greater than the MBT+T volume), the turning lane has the critical (higher) v/c ratio, and increases in MBT traffic only marginally affect the LT v/c ratio since most through MBTs prefer to stay in the through lane.

Once the through traffic grows beyond 650 PCU/hr to exceed the LT volume, the critical v/c ratio shifts to the through lanes. Thus, any increase in MBT+T changes the critical v/c ratio almost proportionally, and the graph turns sharply upward, following the diagonal line. In this region of the graph, MBT traffic would prefer to use the shared LT lane because the v/c ratio in the LT lane is lower than that in the through lane.

This graph can be used to identify the feasible regions for shared queue bypass priority lanes. The feasible boundaries are shown by the two v/c ratio lines for the upper (v/c = 1) and lower (v/c = 0.6) boundary values. The arrows indicate the lowest and highest combinations of through MBT+T traffic that can be accommodated. For example, for any MBT+T volume up to 520 PCU/hr, in combination with any LT volume up to 380 PCU/hr, the maximum v/c ratio is less than 0.6, and the benefits of the shared lane are likely to be very low. Conversely, if the MBT+T volume exceeds 845 PCU/hr while the LT traffic exceeds 640 PCU/hr, then v/c > 1 and the combination becomes infeasible. Thus, the lower and upper feasibility boundaries can be identified as the ranges of 520 PCU/hr to 845 PCU/hr for MBT+T and 380 PCU/hr to 640 PCU/hr for LT traffic, respectively, at which shared queue bypass lanes would be effective. Subsequent graphs (Figures 6 to 8) show these results for gradually decreasing green times, which, as expected, reduce the volume limits at which bypass lanes are feasible.

The final graph (Figure 9) summarises the feasible volume combinations for ease of reference at constant g/C ratios. It illustrates ranges of LT and MBT+T traffic for conditions where v/c ratios are between 0.6 and 1. These boundaries indicate that MBT+T traffic is higher than LT traffic and directly proportional to the v/c ratios. For example, at g/C = 0.5, the feasibility

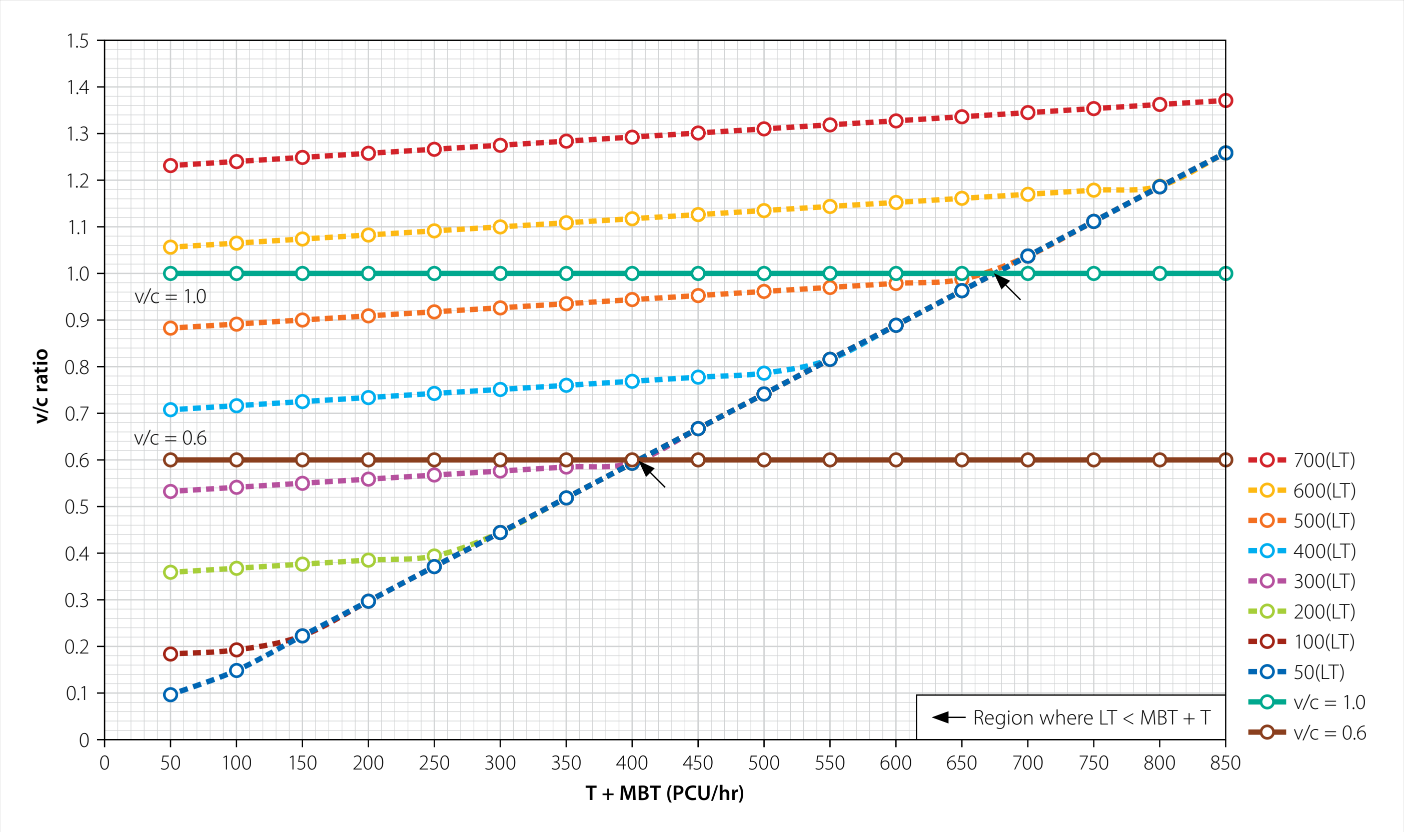

Figure 6 Relationship of v/c ratios and traffic volumes at g/C = 0.40

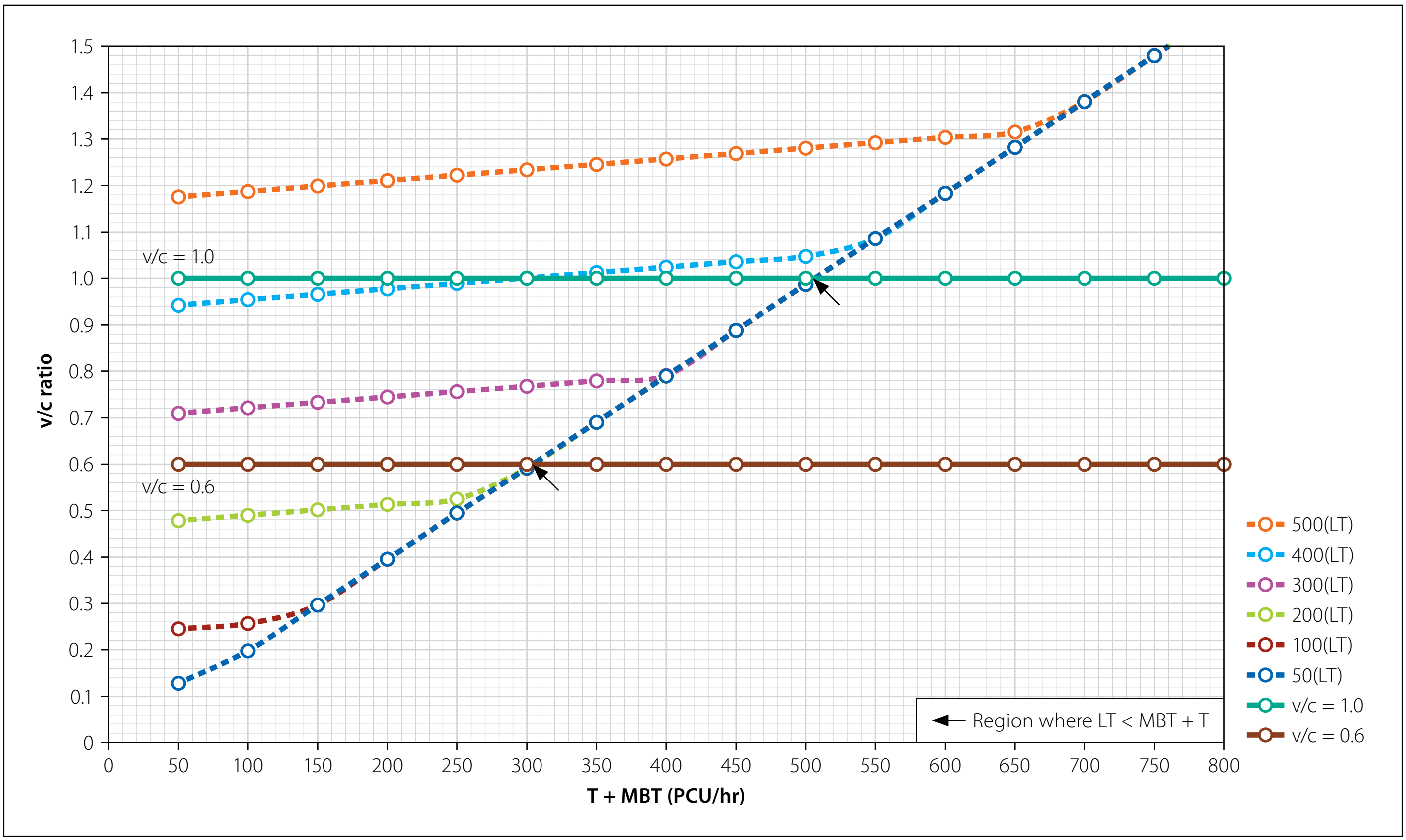

Figure 7 Relationship of v/c ratios and traffic volumes at g/C = 0.30

boundaries for MBT+T traffic range from 520 PCU/hr/lane to 845 PCU/hr/lane, with LT traffic ranging from 380 PCU/hr/lane to 640 PCU/hr/lane. As the g/C ratio values decrease, the feasibility boundaries contract.

Note that the lower feasibility boundary for LT traffic volumes in Figure 9 is derived from the assumed lower limit of v/c = 0.6 imposed by the analysis. If LT volumes are lower than these limits, a shared turning/MBT bypass lane would still be technically feasible, as the MBT vehicles could still utilise the excess capacity in the turning lane for through movement. However, the critical v/c ratio would be less than 0.6, and the benefits of shared lanes would be minimal at these low levels of saturation.

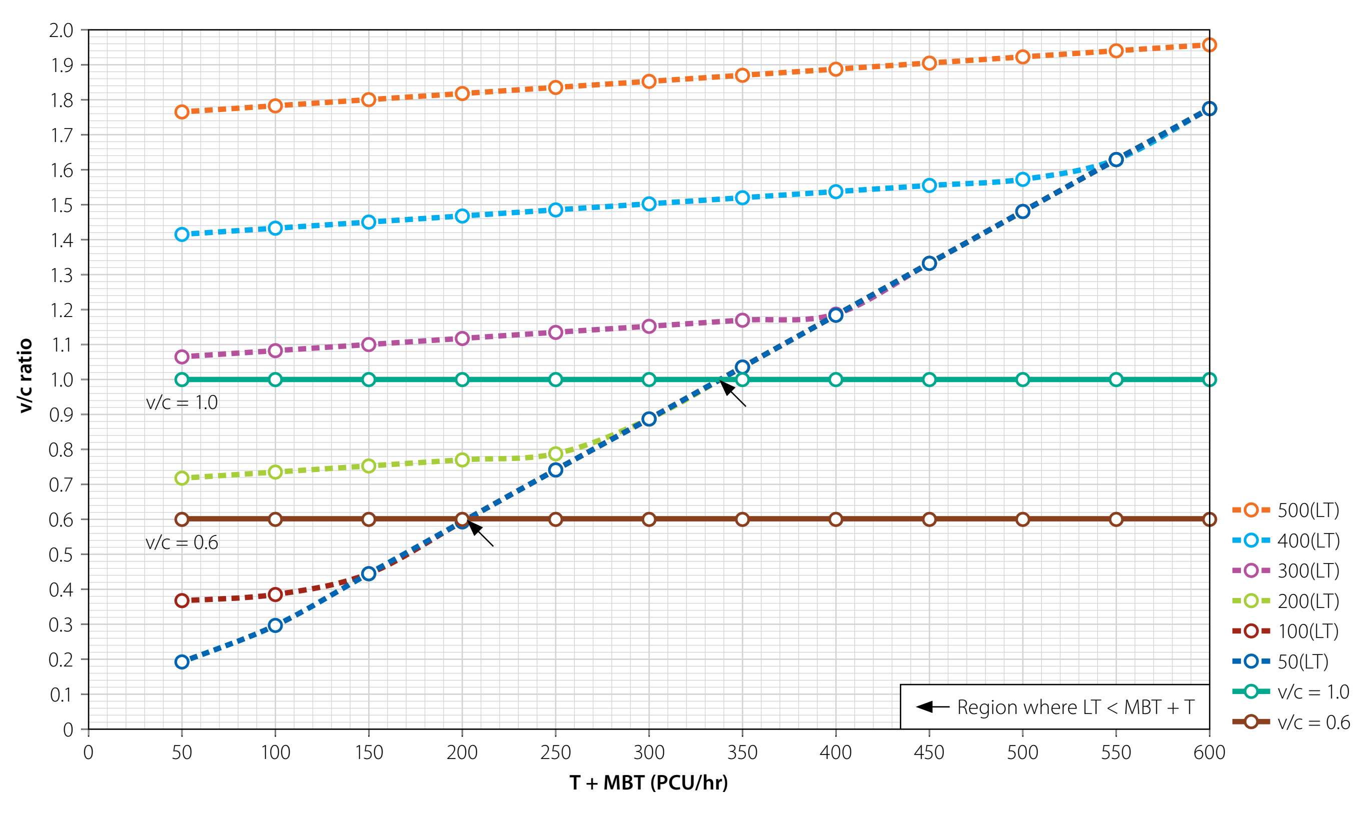

Figure 8 Relationship of v/c ratios and traffic volumes at g/C = 0.20

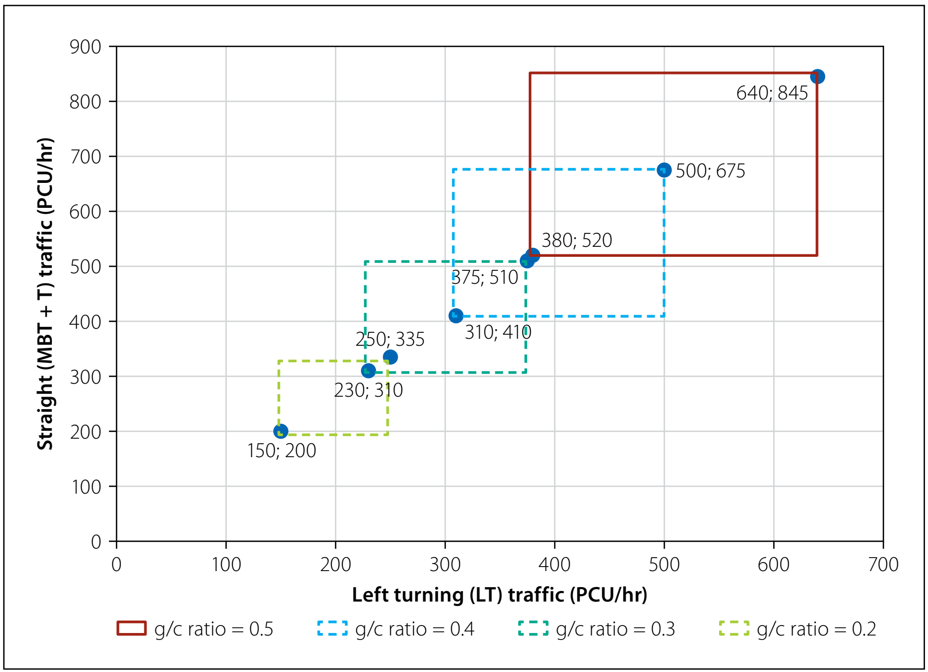

Figure 9 Feasibility boundaries of shared queue bypass lane at various constant g/C ratios

Table 4 Maximum traffic volumes in the shared queue bypass lane

g/C ratio	Maximum traffic volumes (PCU/hr) at v/c= 1		
	LT	MBT+T	Shared queue bypass lane
0.2	250	335	284
0.3	375	250	400
0.4	500	675	568
0.5	640	845	725

Storage lengths

Table 4 summarises the maximum feasible traffic volume combinations in different approach lanes at a v/c ratio of 1. The last column also indicates the resultant maximum volume of combined LT and MBT vehicles shifted into the shared queue bypass lane.

Table 5 provides storage lengths (bottom row) associated with the maximum traffic volumes determined in Table 4 for the shared queue bypass lane calculated using Equation 1 and the assumptions stated earlier. The required storage lengths in the auxiliary lane(s), for situations corresponding to the maximum feasible volumes identified above, range between 65 m and 100 m.

DISCUSSION

The results from both sets of graphs have provided traffic volume feasibility boundaries for a shared queue bypass lane. All graphs indicate that, at a constant g/C ratio, higher v/c ratios are associated with higher volume boundaries for both MBT+T and LT traffic. This aligns with traffic flow theory. The first set of graphs defines feasible volume regions and shows the impact of varying traffic volumes on the overall v/c ratio of the shared queue bypass lane. The effect of reallocating MBT traffic

Table 5 Storage lengths for shared queue bypass lane at v/c=1

g/C ratio	0.2	0.3	0.4	0.5
1-(g/C)	0.8	0.7	0.6	0.5
PCU/hr	284	400	568	725
d x2	12	12	12	12
Number of cycles per hour	45	45	45	45
Number of lanes	1	1	1	1
Storage length (L_{95}) = (m)	60.59	74.67	90.88	96.67
Recommended storage length (L_{95}) = (m)	65	75	95	100

from through lanes to priority lanes is captured by the gradual change in v/c ratios under conditions where LT traffic exceeds through traffic. Additionally, the first set of graphs reveals that v/c ratios increase rapidly and proportionally when MBT+T traffic exceeds LT traffic – a traffic operation condition prevalent at most intersections. This suggests that the v/c ratio for traffic in through (T) lanes is a critical parameter for determining the feasibility boundaries of shared queue bypass lanes.

The graphs also show that feasibility boundaries for both LT and MBT+T traffic increase with higher g/C ratios owing to longer green time intervals. Overall, where LT traffic volumes are less than through MBT+T traffic volumes, the results show that the shared queue bypass lanes' maximum feasibility boundaries for through MBT+T traffic could range from 200 PCU/hr (at g/C ratio = 0.2, v/c ratio = 0.6) to 845 PCU/hr (at g/C ratio = 0.5, v/c ratio = 1.0). Respectively, the maximum feasibility boundaries for LT traffic could range from 50 PCU/hr (at g/C ratio = 0.2, v/c ratio = 0.6) to 640 PCU/hr (at g/C ratio = 0.5, v/c ratio = 1.0).

The information developed from these results provides a preliminary view of the feasibility of implementing a shared turning lane given current volumes and green time ratios. For instance, if the current g/C ratio is 0.2, a combination of LT = 250 PCU/hr and MBT+T = 400 PCU/hr would be infeasible as it falls outside the shaded area (Figure 9) – there is not enough green time to accommodate all the through (MBT+T) vehicles in the shared auxiliary and through lanes. These graphs can also indicate possible remedies. For instance, if the g/C ratio is increased to 0.3, this volume combination becomes feasible (but the v/c ratios of the cross traffic will then change, so the analyst must ensure they remain acceptable). Alternatively, if another through lane can be added, the MBT+T lane volumes will reduce accordingly, which might shift the volume combination into the feasible region.

Finally, the results for storage lengths found that storage lengths for the 95th percentile queue associated with traffic volumes at v/c = 1 ranged from 65 m to 100 m for approaches with g/C ratios of 0.2 to 0.5, respectively. These values can be checked against the available space to indicate the geometric feasibility of implementing shared queue bypass lanes at a site. To prevent traffic blockages in MBT shared queue bypass lanes, it is recommended to consider the storage lengths of adjacent through lanes when designing the full length of the shared queue bypass MBT lane while considering the 95th percentile queue length. In addition to the storage length, the full shared queue bypass lane design should include the taper and deceleration lengths. Further analysis of storage lengths shows a linear relationship between the g/C ratio and maximum storage lengths, with a coefficient of determination (R^2) of 0.954. Figure 10 shows this relationship. The equation may be used to estimate storage requirements for other g/C ratios.

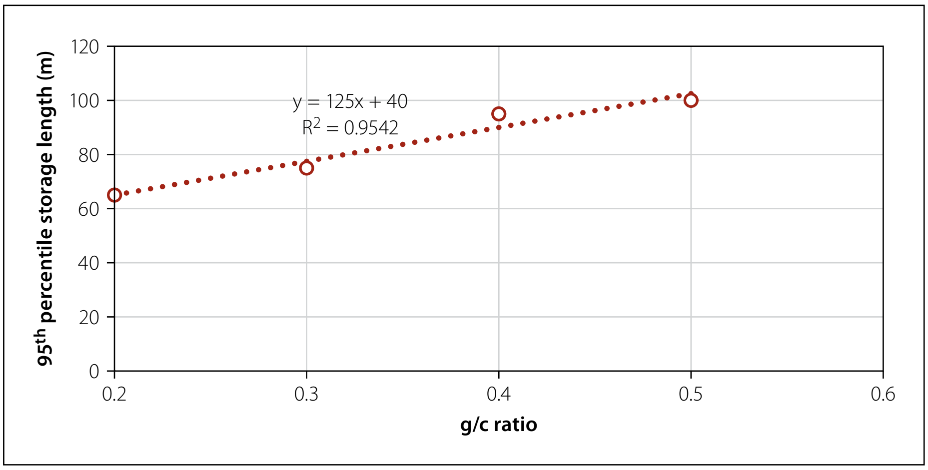

Figure 10 The 95th percentile storage lengths at various g/C ratios of a shared queue bypass lanes at v/c=1

Limitation and suggestions for future research

This study focused solely on the shared queue bypass lane for MBT traffic and did not cover other types of priority infrastructure. The evaluation was based on peak hour traffic volume estimates, excluding off-peak conditions that could determine optimal operational times for shared MBT priority infrastructure at intersections. Additionally, the analysis only considered vehicular traffic, neglecting other types such as pedestrians and motorcycles.

We recommend future research to develop feasibility boundaries for other priority infrastructure types, like dedicated MBT lanes, and to compare those results with this study. Further research should validate the conceptual graphical models using calibrated simulation software and include other traffic types, such as pedestrians, to assess their impact on v/c ratios. Furthermore, future analysis should incorporate full-day traffic counts to determine optimal operational times. Additionally, future research should assess driver behaviour across different cities in South Africa while using MBT priority infrastructure and provide recommendations for signage and lane markings for shared queue bypass lanes.

CONCLUSION

This study presents a method for developing shared queue bypass lanes for enhancing MBT traffic operations without negatively impacting overall intersection performance. It outlines feasibility boundaries through the analysis of lane capacities at pre-timed signalised intersections. Using the HCM analytical method, the study redistributes traffic volumes and examines the relationships between v/c ratios, straight traffic, LT traffic, and g/C ratios after implementing MBT priority infrastructure. Graphical representations illustrate the feasibility boundaries, indicating that through MBT traffic volumes of 20 PCU/hr to 85 PCU/hr are appropriate for shared queue bypass lanes, provided LT traffic volumes range between 50 PCU/hr and 640 PCU/hr, depending on green time.

The study also provides storage length estimates for shared queue bypass lanes based on maximum traffic volumes from graphical models at constant v/c ratios. Maximum storage lengths of 65 to 100 were estimated at g/C ratios between 0.2 and 0.5 at v/c ratios of 1. A linear relationship between storage length and g/C ratio was developed for estimating storage lengths for the 95th percentile queue associated with the shared queue bypass lane.

The demonstrated method for assessing the feasibility of priority treatments may also be adapted for examining other priority treatments, such as queue-jumping and dedicated lanes. The graphical representations can serve as a basis for quick identification of eligible intersections before more resources are spent on data collection and detailed analysis using traditional methods for signalised intersection design.

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