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Priority infrastructure for minibus-taxis: An analytical model of potential benefits and impacts

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Many governments in the global south are grappling with challenges of improving the quality of informal transport, and an inability to pay for service improvements. This paper asks the question whether efficiency benefits might be gained through strategic implementation of once-off infrastructure interventions providing priority to informal vehicles at intersections. We note that informal drivers already indicate this demand through (illegal) driving behaviour in traffic. We use a drone to observe indicative behaviours among minibus-taxi drivers in South Africa. We identify interventions that would formalise this behaviour: a single lane pre-signal strategy, queue-jumping lane, and dedicated public transport lane. The objective of the paper is to quantify the potential economic impacts of such treatments on minibus-taxi operators, passengers and other road users. The findings indicate that substantial savings could be realised in terms of travel time, user cost, and operating cost to taxi passengers and drivers without additional costs being incurred by other road users. The single-lane pre-signal strategy, the queue-jumping lane and the dedicated taxi lane saw a decrease in total hourly cost of 12%, 14% and 30% respectively, including construction cost, user cost, and agency cost, indicating a net social benefit. If part of these savings were passed on to passengers, priority infrastructure could serve as an implicit subsidy to public transport users.

INTRODUCTION

The paratransit industry in South Africa has grown from a modest provider of public transport to the largest supplier of mobility to the urban public. Small-scale ownership of minibus-taxis enabled the industry to develop in an adaptive and flexible way where the fares remain low, and the services respond rapidly to any change in need from the passengers (Jennings & Behrens 2017).

Recent initiatives to overhaul South Africa's entire public transport system, partly to address the deficiencies of the minibus-taxi system, have often resulted in a complex set of formal and paratransit operations which are independent of each other, subject to a regulatory framework that is disconnected (Salazar Ferro *et al* 2012). There have been some efforts to improve the infrastructure for minibus-taxi facilities and operations, including undercover loading areas, public toilets, and office space (Schalekamp & Klopp 2018). In the early 2000s the City of Johannesburg took a step towards implementing dedicated taxi lanes as a part of its Strategic Public Transport Network (SPTN), but this was abandoned in favour of Bus Rapid Transit (BRT). However, the realities of the slow and expensive roll-out of BRTs, coupled with the realisation that the minibus-taxi has a continuing role to play in a hybrid public transport system, has turned the attention of some authorities back towards dedicated infrastructure for this mode.

Unfortunately, the evidence base on which to find the planning and design of priority infrastructure for minibus-taxis is very thin. Qualitative studies have documented the response of the minibus-taxi industry to proposed changes and formalisation of the industry fairly well (Schalekamp & Behrens 2010; 2013). Research on the driving behaviour of minibus operators is limited. Some simulation tools have been developed to help model driver behaviour and route evolution of taxis (Gu *et al* 2012; Hager *et al* 2015; Neumann *et al* 2015; Zheng *et al* 2020). However, no systematic exploration of alternative infrastructure-based interventions for minibuses has been done. It is the contention of this research that such interventions, when applied judiciously,

Keywords: paratransit, minibus-taxi, economic model, priority infrastructure, operating cost

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may raise the overall cost-effectiveness of minibus operations, and deliver benefits to users and operators. Moreover, it may be possible to do so without substantially degrading the level of service offered to other road users. Accordingly, the aim is to quantify, using relatively simple mathematical modelling, the benefits that minibus-taxi operators and passengers receive when they skip traffic queues at intersections during congested periods of the day. An analytical approach was developed for a single bi-directional corridor with intersections, avoiding for now the complexities of simulating entire networks. The model is a first effort to derive metrics for the costs and benefits of operators, passengers and private car users, and does not address issues of safety or design.

The paper starts with the observation that minibus-taxi drivers already display driving behaviour that simulates priority access, even in the absence of such infrastructure (and therefore often under unsafe and illegal conditions). We use remote detection to identify such behaviour and suggest intersection treatments to formalise such priority access. Then follows a description of the public transport priority measures (including pertinent literature), of the analytical model used to evaluate them, and the results. Lastly, we present conclusions and recommendations for implementation and further research.

ILLUSTRATIVE OBSERVATIONS OF TAXI DRIVER BEHAVIOUR

Minibus-taxi operators often try to cut corners (literally and figuratively) in their efforts to save time – this is mainly due to pressure being put on them by their passengers and their need to survive financially. The need to maximise income by finding more passengers and reducing cycle times to complete more round trips during the peak period means that it is often in their best interest to weave their way through traffic to get ahead of congestion (Govender & Allopi 2007).

With the use of an unmanned aerial vehicle, commonly referred to as a "drone", this behaviour was observed along various corridors in the Pretoria area. This is meant as an observational study to find exemplars of such behaviour and their implications, rather than an exhaustive survey of behaviours. The following three cases illustrate the delay advantage that operators try to gain at intersections with long queues.

Figure 1 Minibus-taxi creating own informal priority, Case 1

Figure 2 Minibus-taxi creating own informal priority, Case 2

Figure 3 Minibus-taxi creating own informal priority, Case 3

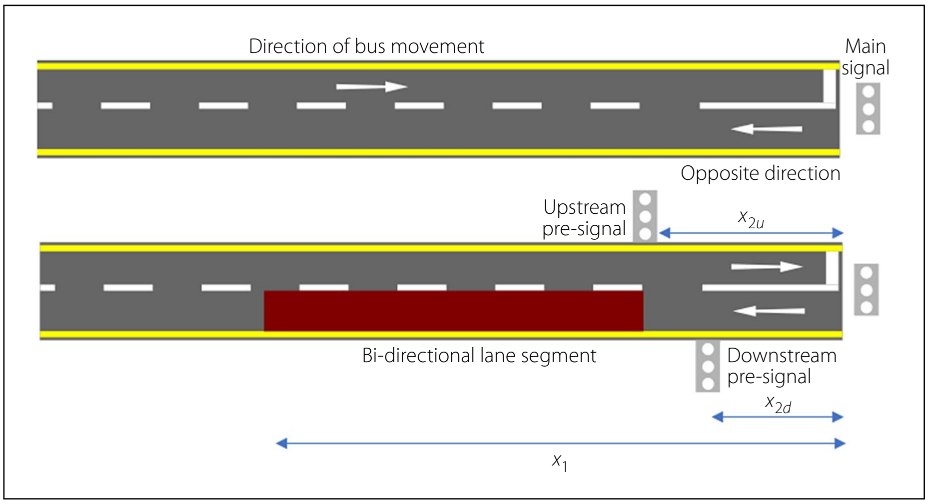

Figure 4 (a) Intersection with single-lane approaches, (b) pre-signal strategy (adapted from Ilgin Guler *et al* 2015)

Case 1 (queue-skipping behaviour)

In Figure 1 a minibus-taxi on a through-movement is observed driving in the right-turn lane. After the traffic signal turns green, the taxi is seen cutting into the lane adjacent to it, thereby effectively skipping eight vehicles in the queue – this is due to the adjacent, right-turning lane having a shorter queue length. The behaviour is like a queue-jumping lane type of infrastructure, and jumping past such a long queue of vehicles saves this particular taxi approximately 24 seconds.

Case 2 (queue-skipping behaviour)

The second case, as Figure 2 illustrates, is like the first in that the operation of an informal queue-jumping lane is observed. This time, however, two minibus-taxis skip the queue as soon as the traffic signal turns green. From their behaviour the taxi travelling behind attempts to push in first in the centre lane after which allowing the taxi in front of it to do the same. This illustrates the sense of community minibus-taxi operators have, attempting to help the other out when the opportunity arises. In this case, the two taxis skip a queue of over 12 vehicles and can save approximately 66 seconds because they avoid being stuck in the overflow queue at the end of the cycle.

Case 3 (opposite-lane driving behaviour)

In the final case observed, as illustrated in Figure 3, a minibus-taxi is seen travelling in the lane of the oncoming traffic after which it makes a right turn. This behaviour is more dangerous than the previous two cases. Only one second is saved in this process, as the queue that forms at the intersection only amounts to the single vehicle travelling in front of it.

Formalising the driving behaviour as depicted in the cases illustrated might, in theory, reduce the delay experienced by minibus-taxi drivers and passengers, while mitigating the problems with safety and habitual flaunting of traffic rules. In the next section three potential strategies are identified to formalise priority to public transport vehicles.

PUBLIC TRANSPORT PRIORITY MEASURES

Public transport priority measures are interventions made to provide public transport vehicles with a competitive time advantage over private vehicles. These interventions can be either physical or policy-related, like a bus-only roadway or legislation requiring private vehicles to yield to buses (Halifax Regional Municipality (Canada) 2018). This research considers the currently available public transport priority measures that have proved to be effective in the public transport sphere, particularly pertaining to buses. These infrastructure forms include the single-lane pre-signal strategy, queue-jumping lane, and dedicated public transport lane.

Kerbside bus stops

The most basic form of infrastructure intervention is the construction of passenger loading bays. Although much provision has been made for bus stops, little attention has been paid to providing stopping facilities for taxis. Bus service times at a bus stop occupy a large proportion of the total operational time the bus spends on the road, and the occurrence of queues forming at the entry and departure area of a kerbside bus stop is frequent. Regarding the bus stop design, bus size, and congestion, Tirachini (2014) stated that buses have the lowest capacity at the bus stop component of a bus route, and the first element subject to congestion.

Single-lane pre-signal strategy

Ilgin Guler *et al* (2015) proposed a strategy whereby buses are given priority at signalised intersections with single-lane approaches by adding traffic signals to the road such that a bus can jump a portion of the car queue by making use of the travel lane in the opposite direction. Two additional pre-signals are placed upstream at a distance x_{2u} km and downstream at a distance x_{2d} km from the main signal. These two signals then operate together to create an intermittent bus priority lane. When there is no bus present both the pre-signals will remain green, and cars will be able to discharge through the intersection normally. When a bus approaches and reaches a distance x_1 km from the main signal, both pre-signals at x_{2u} and x_{2d} turn red, indicating to cars from both directions to stop. The bi-directional segment is now cleared, and the bus is free to drive onto the opposite lane and travel without being impeded until it can merge back onto its original lane. Figure 4 (p 55) illustrates the setup.

The authors quantified the delay savings that the buses achieved, as well as the negative impact that cars experienced when this method was applied. The study found that, in the under-saturated case, significant bus delay savings and/or improved system-wide delays overall can be achieved with single-lane approaches under the following conditions:

- V/C less than 0.85
- A distance of at least 7 m between the pre-signal location and the intersection
- When a turning ratio, from the cross-street, of less than 25% is observed.

A theoretical analysis of an over-saturated case, however, suggests that, although the average bus delay savings can be up to 30 seconds, the loss in capacity can be as much as 25%.

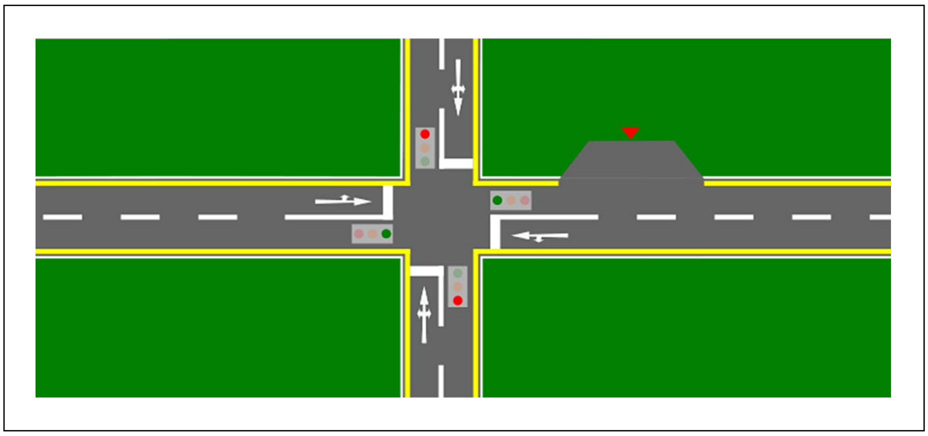

Figure 5 Schematic representation of the kerbside taxi stop

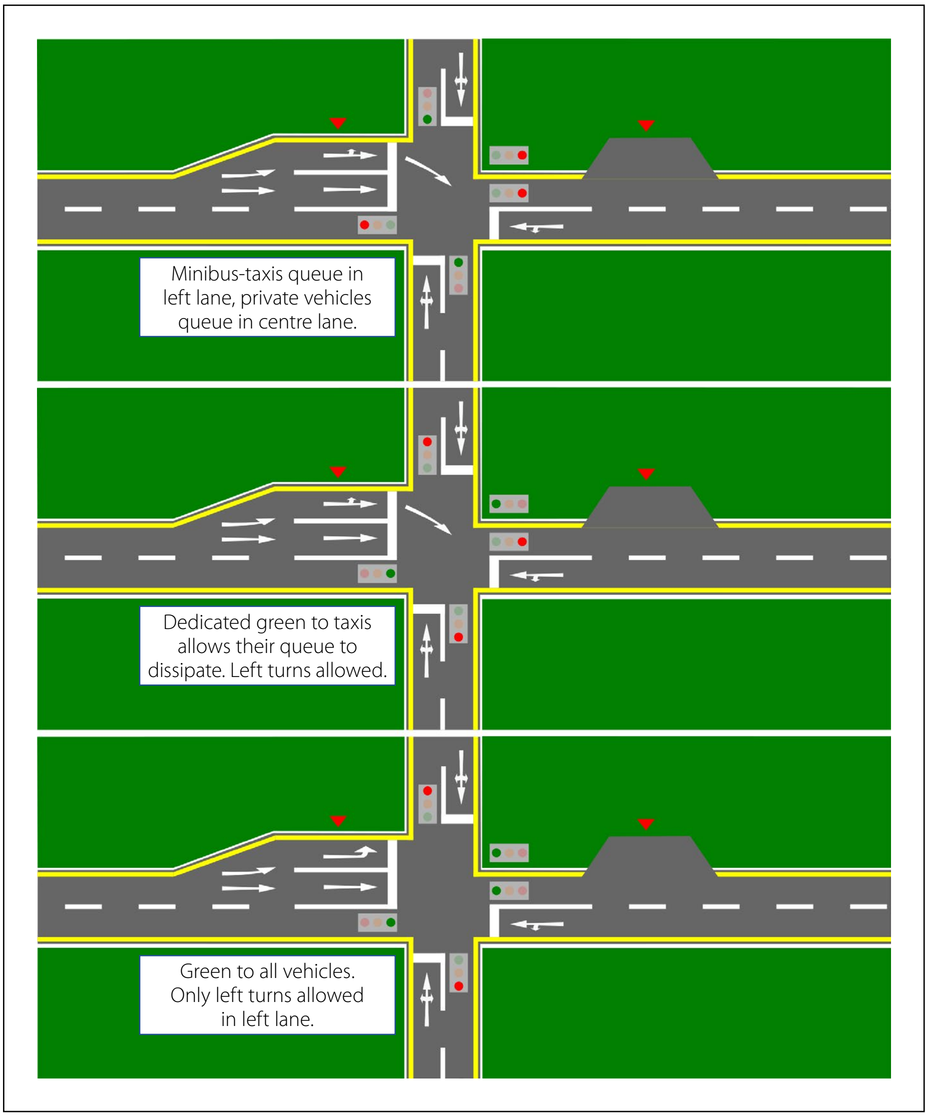

Figure 6 Schematic representation of the queue-jumping lane

Queue-jumping lane

Extensive research has been conducted in the functioning and operation of queue-jumping lanes (Bhattacharyya *et al* 2019; Zhou & Gan 2009). A queue-jumping lane allows the high-occupancy vehicle to bypass queued traffic, giving them the opportunity to gain an advantage at a signalised intersection. As the vehicle approaches the intersection, it leaves the queue and enters the queue-jumping lane. A priority signal, thereafter, allows the queue to clear before the main green stage commences.

Zlatkovic *et al* (2013) evaluated the individual and combined effects of a queue-jumping lane and public transport signal priority on the performance of a BRT (Bus Rapid Transit) system. They found that for each case, namely, queue-jumping, public transport signal priority, and a combination of the two, the BRT is offered significant benefits whereas certain impacts are imposed on vehicular traffic. The greatest benefit to the BRT is observed with the combination scenario – the BRT travel times are reduced by between 13% and 22%, there is a significant improvement of the progression of the BRT vehicles through the networks, intersection delays and waiting time are reduced, speed increases significantly by 22%, and the travel time, reliability, and headway adherence are better than the other two scenarios.

The largest drawback in the implementation of the public transport preferential treatment is the deterioration of the vehicular traffic performance on a network-wide level, the majority of which was observed on cross-streets.

Dedicated bus lane

Dedicated bus lanes fundamentally improve the effectiveness of public transport when

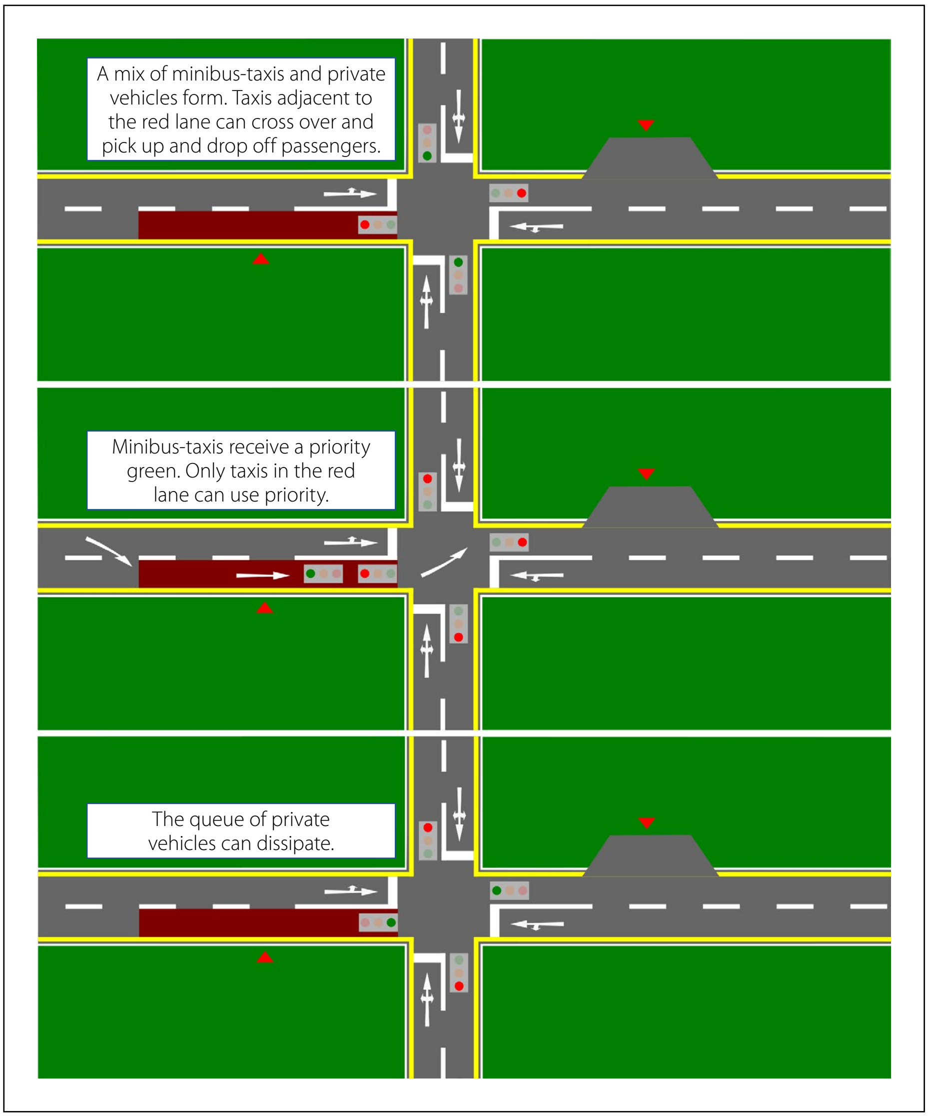

Figure 7 Schematic representation of the single-lane pre-signal strategy

implemented at a city level (Brasuell 2019; Glambrone & Acitelli 2019). Ben-Dor *et al* (2018) exploited MATSim's capabilities to emulate how a traveller would adapt to varying transportation possibilities and found that not only do dedicated bus lanes result in the same public transport characteristics to be observed during peak hours as with off-peak hours, but an increase of 20% in public transport use was also observed during congested conditions.

Stamos *et al* (2012) evaluated the HOV (high occupancy vehicle) lane in the central business district of Thessaloniki, Greece, where the primary objective was to alleviate the impacts of traffic and congestion in the city. The implementation of the HOV lane saw a 6% drop in traffic due to the decreased number of vehicles transporting more than two passengers that can use the lane. The decrease was partially balanced by the demand that was induced due to the attractiveness of the lane. The slight decline in traffic, together with the prohibited turning movements in the lane, caused a 62% reduction in delay and an increase in speed of 129%.

MODEL DESIGN

Four forms of infrastructure are modelled, namely, a kerbside taxi stop, a queue-jumping lane, a single-lane pre-signal strategy, and a dedicated taxi lane. The objective of the model is to quantify the high-level economic impact that the selected priority infrastructure would have on the paratransit operators, taxi passengers, other road users, and the agency providing the infrastructure. This is in keeping with the definition of total cost as including costs to both users and operators/infrastructure owners, consistent with the notion of net social welfare. This means that the model will consist of four main sections which include:

1. The signalised intersection design which determines the cycle length, red phase length, and green phase length.
2. The user cost which entails the time passengers in the minibus-taxis, as well as private vehicle owners, spend on the road.
3. The operating cost, which is based on time spent on the road as well as the distance covered and includes all the costs associated with operating a minibus-taxi or a private vehicle.
4. The capital cost, which is the cost associated with constructing each of the four forms of public transport infrastructure.

Model parameters

The intersection consists of a north-south and an east-west two-lane road. The minibus-taxis and regular vehicles travel mixed, as there is no priority for the paratransit vehicles at the intersection pertaining to the kerbside stop. This form of infrastructure will be considered as the base case against which to compare all the subsequent forms of priority infrastructure. Figure 5 illustrates the schematic model upon which calculations are based. All taxi stops in the subsequent figures are indicated with a red triangle. For simplicity's sake only the west-to-east and north-to-south movements are modelled, but the results can easily be generalised for all directions.

The second public transport priority infrastructure, the queue-jumping lane, allows minibus-taxis to skip the entire queue at the intersection by providing them with a dedicated section of road. During the red cycle phase, taxis can drop off and pick up travellers in the dedicated lane but are not able to make stops during the priority green phase or the all-green phase. For this purpose, a far-side kerbside stop is retained to allow for loading and unloading during the green cycle phase. The percentage of taxis stopping to pick up or drop off passengers is based on an input value in the model. The operation of the infrastructure in its three stages is illustrated in Figure 6.

The third priority infrastructure, the single-lane pre-signal strategy, provides taxis with a time advantage without incurring significant construction costs. The length of the priority section of road is designed to account for the number of private vehicles that queue over the duration of the east-west green phase. Only taxis adjacent to the priority section of road are permitted to use it to gain a time advantage. The three phases of the operations are illustrated in Figure 7. It is noted, however, that boarding or alighting a minibus-taxi in the middle of the road is dangerous, and that a raised kerb in the centre of the road

Table 1 Input variables used in the signalised intersection design

Variable	Description	Value used
Average delay per vehicle (private vehicles), d_{avg}	■ Used as an input value to determine the red cycle time for each case. ■ In the infrastructure forms where minibus-taxis receive a priority signal, their average delay is calculated separately.	12 seconds
Cycle length in seconds, C	■ The time to complete a full traffic intersection cycle.	80 seconds
Arrival rate in vehicles/second, v	■ The arrival rate was based on traffic counts that were carried out on a road corridor where different transportation modes operate.	Varied (see Table 2)
Departure rate in vehicles/second, s	■ Minibus-taxis and private vehicles are assumed to have the same saturation flow rate.	0.5 veh/s (1 800 veh/h)

may have to be constructed to account for this issue.

The final priority infrastructure, the dedicated taxi lane, is expected to provide public transport with the greatest amount of time saving whilst minimising the delay experienced by regular traffic. The representation of the dedicated taxi lane is illustrated in Figure 8.

Signalised intersection design

The design of the intersection forms the base of the model development – the signal plan determines the waiting time at the intersection, as well as the queue lengths that form as a result. These values are then used to determine the subsequent user costs and operating costs.

Table 1 provides the input variables used in the signalised intersection design. Each variable is briefly explained.

A key assumption is that the average delay for private vehicles is kept constant at 12 seconds, corresponding to a Level of Service B. In normal traffic analysis the delay is estimated as a function of arrival and departure flow rates, red times, and cycle lengths. However, we turn this analysis around by fixing the delay, and calculating the red time that is needed for a given cycle length and departure rate. This imposes limits on the capacity of the intersection, but allows us to focus on cases where the minibus-taxis are provided with some form of priority without deteriorating conditions for private vehicle users.

Table 2 summarises the arrival rates assumed for private vehicles and minibus-taxis at high and low-flow scenarios, obtained from a typical corridor in the Pretoria CBD.

For the base case (kerbside taxi stop) the average delay per vehicle is given by the following standard equation for undersaturated signal approaches (Transportation Research Board 2013):

$$d_{avg} = \frac{r^2}{2c\left(1 - \frac{v}{s}\right)} \qquad (1)$$

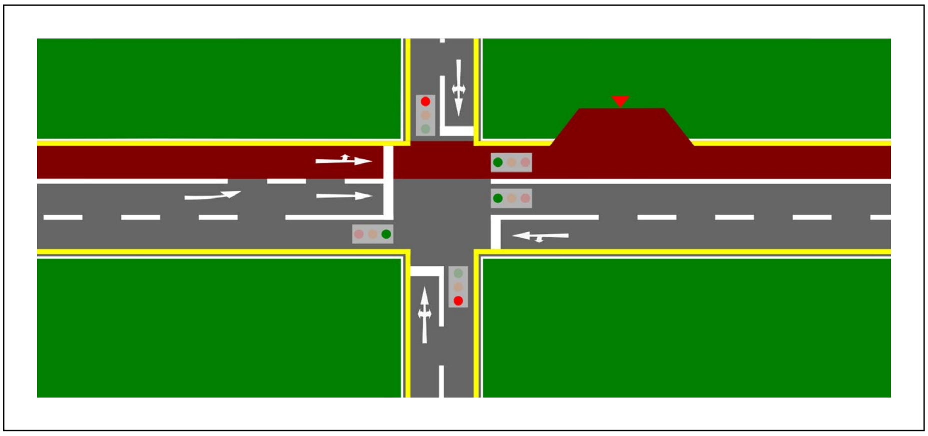

Figure 8 Schematic representation of the dedicated taxi lane

Where:

r : Effective red time for a traffic movement in seconds
C : Cycle length in seconds
v : Arrival rate in vehicles/seconds of taxis and private vehicles
s : Departure rate in vehicles/seconds

Rearranging in terms of r gives an expression for the effective red and effective green times:

$$r = \sqrt{d_{avg} \cdot 2C \cdot \left(\frac{v}{s}\right)} \qquad (2)$$

$$g = C - r \qquad (3)$$

The queueing diagrams for both the high and low-flow cases in the west-to-east direction are shown in Figure 9.

The maximum queue and approach capacity is easily estimated from the graphs. Over the 23-second red phase of the high-flow traffic case, a queue of 9.3 vehicles forms from a combination of private vehicles and minibus-taxis. For the low-flow case, the corresponding red time and queue length are 36 seconds and 6.2 vehicles respectively. Note that, for the high-flow case, the entire queue just dissipates by the end of the green; this delivers a lower performance boundary for undersaturated operations. As a first approximation we ignore stochastic effects that might cause extra delay due to occasional oversaturation.

For the queue-jumping lane and the single-lane pre-signal strategy, the queuing diagrams depict two red phases (one for taxis and one for private cars) and two green phases (one for taxis only and one for all vehicles) (Figure 10). The same design applies to both forms of infrastructure, as their methods of providing minibus-taxis with a pre-signal priority are similar. In the red phase both the minibus-taxi (t) and the private vehicle (c) queues start to build. The minibus-taxis then receive a priority green of g_t seconds, after which the minibus-taxis and private

Table 2 Arrival rate of private vehicles and minibus-taxis

Traffic flow rate	Private vehicle arrivals v_c (veh/h)	Minibus-taxi arrivals v_t (veh/h)
High-flow case (east-west)	1 090	350
Low-flow case (east-west)	534	81
Flow (north-south)	534	81

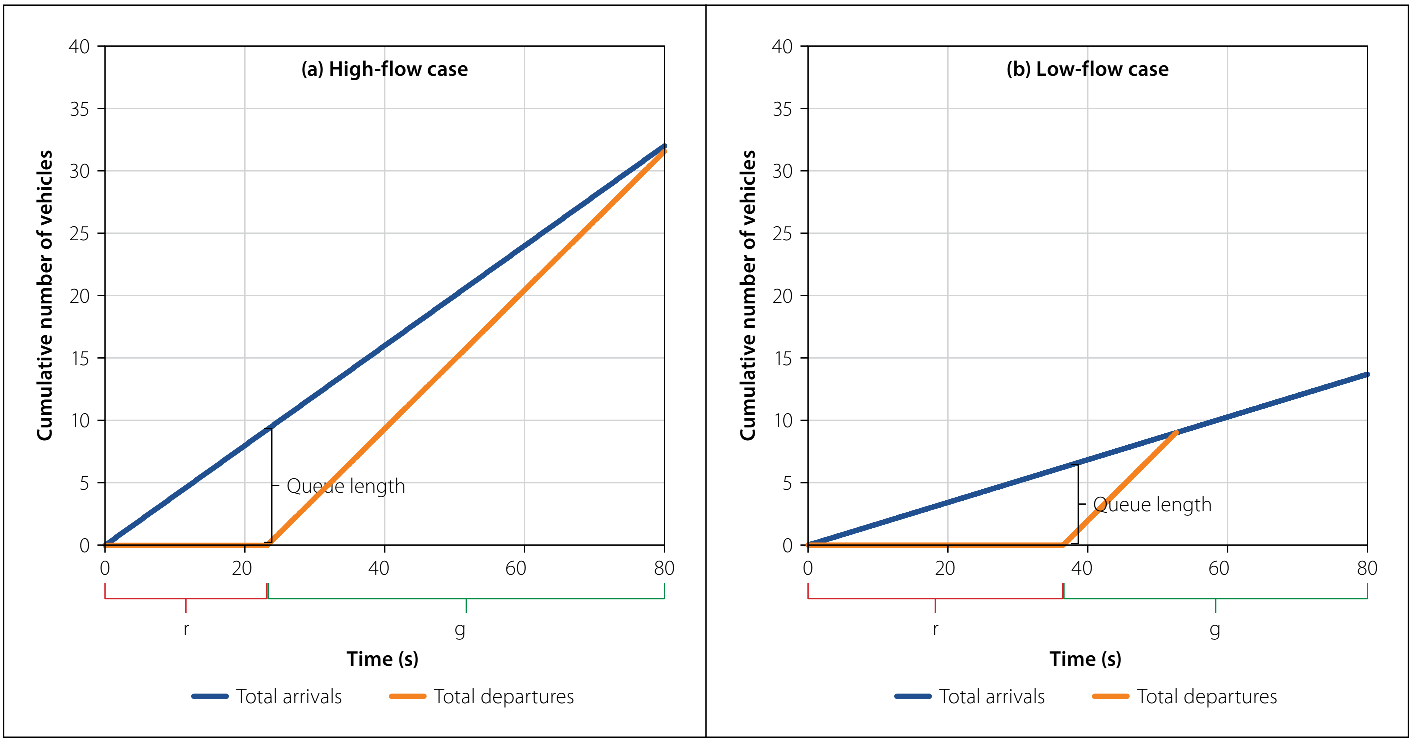

Figure 9 Signalised intersection queuing graph for the kerb-side taxi stop ("g" denotes green, and "r" denotes red)

vehicles travel in the same lane as mixed traffic. This introduces an inflection point on the arrival curve after r_c seconds, corresponding to the sum of the private vehicle and taxi arrival flows. As before, at these flow rates the entire queue dissipates by the end of the cycle.

The dedicated green phase for the minibus-taxis is not granted at the cost of green time for the private vehicles, but rather by shortening the red time. This reduces the green time for the cross traffic in the north-south direction, as well as its capacity, and possibly its level of service. This reduction is easily estimated using the cycle length and red and green times.

The length of the red cycle for mixed traffic is once again determined to keep the average delay at 12 seconds per vehicle. Due to the inflection point on the arrival curve, the delay is no longer given by Equation 1, but can be shown to be equal to:

$$d_{avg} = \frac{r_c v_c}{2(v_c + t)} \qquad (4)$$

Where:

r_c : Red phase for cars (and mixed traffic after priority green phase for minibus-taxis) (s)

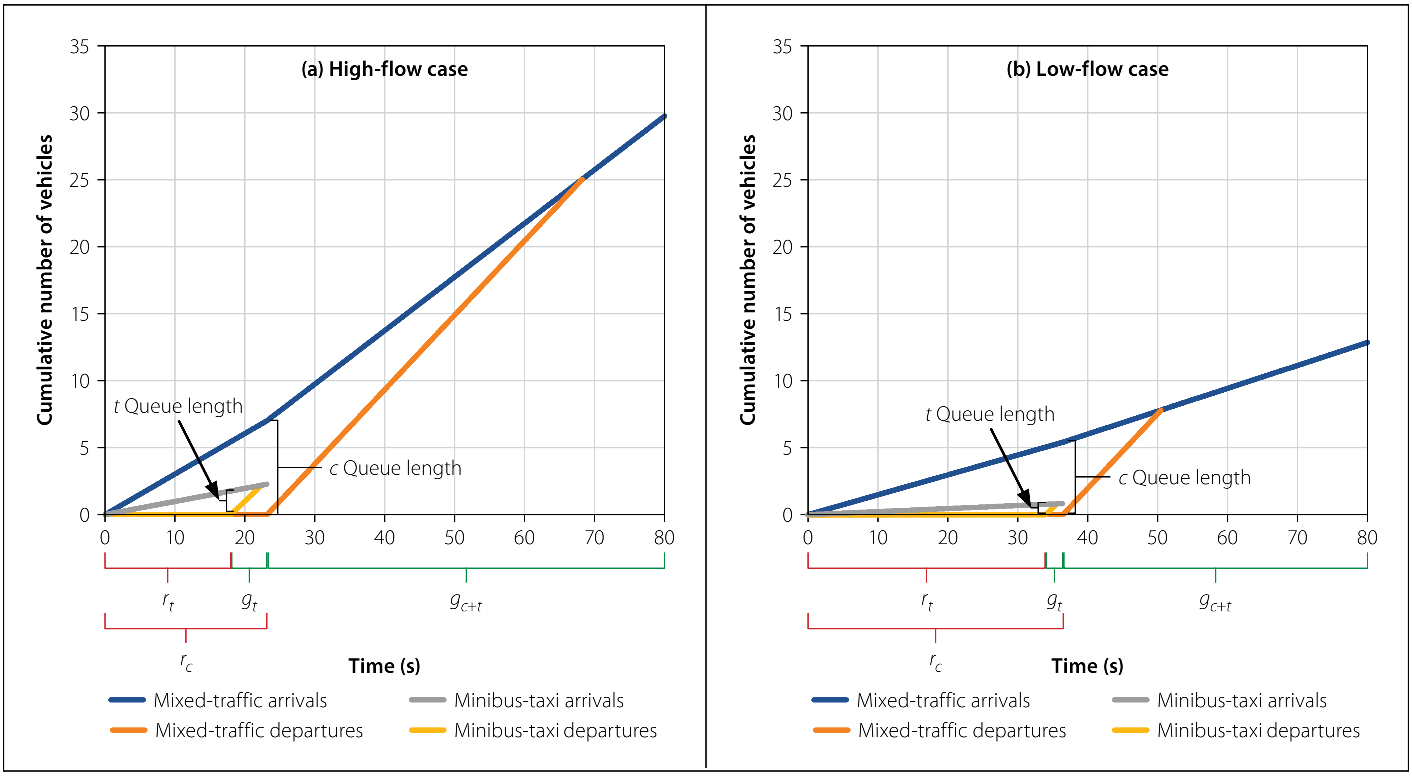

Figure 10 Signalised intersection queuing diagram for the queue-jumping lane and the single-lane pre-signal strategy ("g" denotes green, "r" denotes red, "c" denotes cars, and "t" denotes taxis)

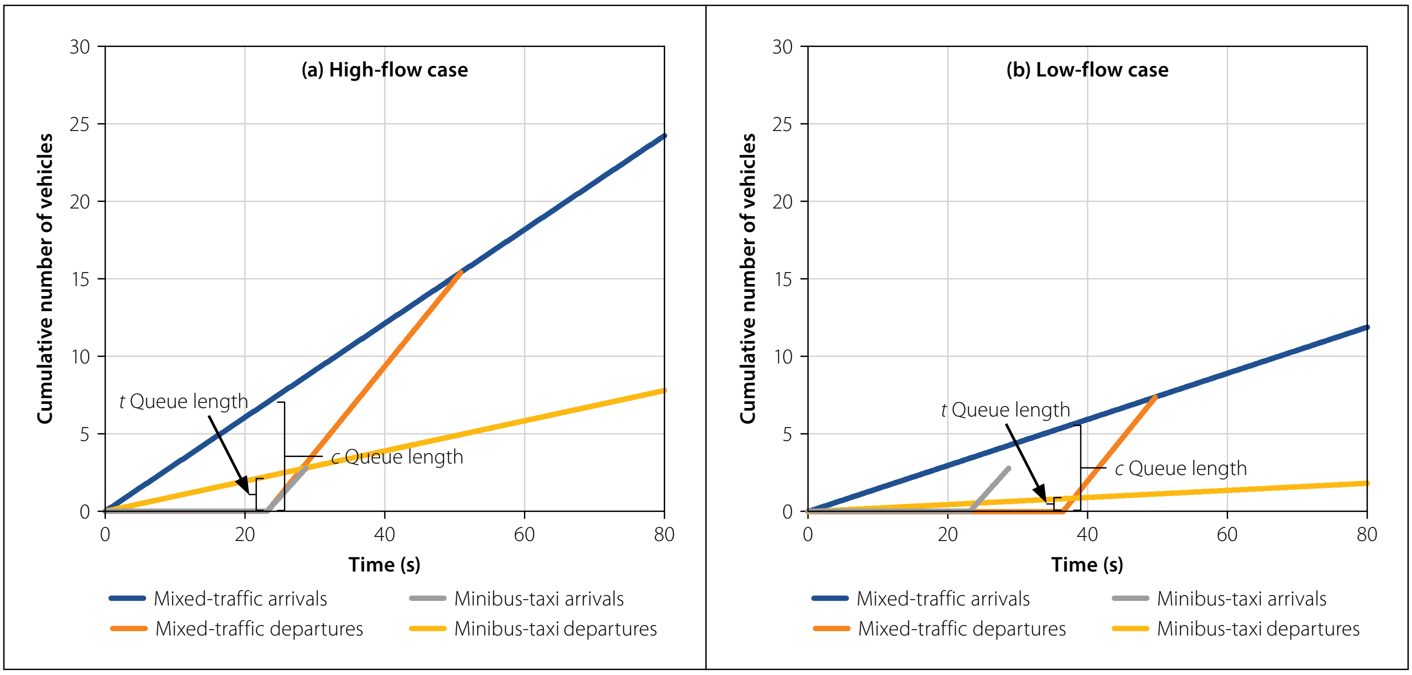

Figure 11 Signalised intersection queuing diagram for the dedicated taxi lane ("g" denotes green, "r" denotes red, "c" denotes cars, and "t" denotes taxis)

v_c : Arrival rate in vehicles/second for cars
r_{c+t} : Combined arrival rate in vehicles/second for cars and minibus-taxis

With d_{avg} known, the length of the red phase for mixed traffic r_c can be extracted. The length of the dedicated green for taxis is set simply at the value required to discharge the taxi queue, thus $r_t = r_c - r_c(v_t/s)$. Average delay for minibus-taxis is now a combination of the delay of taxis using the dedicated green signal, and the delay of taxis arriving after the dedicated signal ends. The former delay value is estimated using Equation 1 with $r = r_t$, $v = v_t$, and $C = r_c$. The latter delay comes from calculating the area between the arrival and departure curves for the combined green phase and dividing it by the total arrivals during this phase which follows Equation 1.

Figure 10 shows that, for the high-flow case, providing minibus-taxis with a pre-signal priority of 4.2 seconds effective green (g_t) time allows an average of two taxis to skip the queue over each cycle and for the queue to dissipate. The length of the section of road on which minibus-taxis queue should be at least 11 m long to accommodate these queues. Over the first part of the cycle, taxi delay averages 10.8 seconds, dropping to 8.8 seconds in the mixed-traffic phase.

The queuing diagram for the dedicated taxi lane intersection is shown in Figure 11. The additional lane means that taxis and private vehicles have independent arrival and departure curves. The red time is still determined from Equation 1, keeping d_{avg} at 12 seconds for private vehicles. The delay for taxis is lower due to their lower arrival rate.

The private vehicle queue of 13.7 vehicles on average dissipates after 47 seconds, whereas the minibus-taxi queue of three vehicles per cycle dissipates after 27 seconds.

User cost

Determining the user cost depends on the relevant vehicle characteristics for both private vehicles and minibus-taxis. Table 3 shows typical values determined from observations performed on traffic footage obtained in the Hatfield area in Pretoria, or as suggested by relevant literature.

The user cost for minibus-taxis consists of the sum of the estimated service time, waiting time at the red traffic signal phase, time taken to accelerate and decelerate, and travel time. For cars, this variable is the same as that for minibus-taxis, except service time is excluded. Taxi fares are excluded to avoid double-counting of operating costs. The total travel time for minibus taxis is given by the equation:

$$TT = T_s + T_r + T_a + T_t \tag{5}$$

Where:

T_s : Total service time (in hours)

Table 3 Input variables used in calculating user cost

Variable	Description	Value used
Acceleration and deceleration rate, *a*	Rates are assumed to be equal and the same for private vehicles and minibus-taxis	3.5 m/s^2
Vehicle capacity, *pax*	The number of passengers transported by the vehicle	Cars: 1.5 passengers Minibus-taxi: 18 passengers
Passenger handling time, *H*	The passenger handling time includes the time a passenger takes to board and alight a minibus-taxi	8 seconds/passenger
Time for opening and closing doors, C_d	Value assumed to equal that of a BRT	3 seconds (Transportation Research Board 2013)
Speed on entering the kerbside stop	This speed forms part of the calculations determining the total service time of a minibus-taxi on the kerbside stop type of service infrastructure	3 m/s

Table 4 Private vehicle and minibus-taxi user income group, value of time, and proportion

Income group	Value of time (VOT)	Proportion (%)
Private vehicle user		
Low income	R4.00*	7.4
Middle income	R18.00	18.5
High income	R31.00	74.0
Minibus-taxi user		
Low income	R4.00	28.1
Middle income	R18.00	45.9
High income	R31.00	26.0

* The exchange rate on 12/02/2020 was 0.068 USD to 1 ZAR.

Table 5 Input variables used in calculating operator cost

Variable	Description	Value used
Vehicle operator salary, V_s	The monthly salary of a minibus-taxi operator	R20 000.00/month
Tyres and other expendables, V_t	Contingencies and the cost of tyres per month	R5 735.00/month
Vehicle maintenance, V_m	The cost of maintaining a minibus-taxi over a month period	R4 303.00/month
Facility maintenance, V_f	The cost to rent the premises where the minibus-taxis are stored, costs per month	R811.00/month
Administrative costs, V_a	This cost consists of unemployment insurance fund, a cell phone payment, and a bookkeeping cost	R1 168.00/month
Supervision and control centre, V_c	Satellite tracking and the cost of the vehicle	R1 104.00/month
Cost of fuel, F_c	The price as of the 1 June 2019	R16.48/ℓ (Automobile Association 2019)
Fuel consumption, f_c^t, f_c^c	The travelling component of fuel consumption	7 ℓ/100km for private vehicles 12 ℓ/100km for minibus taxis (Automobile Association 2013)
Fuel idling, f_i^t, f_i^c	The idling component of fuel consumption	1.2 ℓ/hour for private vehicles 1.5 ℓ/hour for minibus-taxis
Vehicle-Hours, *VH*	The number of hours that a minibus-taxi travels in a month	176 hours
Vehicle-Distance, *VD*	The distance that the average minibus-taxi operator travels in a month	18 000 km (Department of Transport 2008)

T_r : Wait time at red intersection phase (in hours)
T_a : Time to accelerate and decelerate (in hours)
T_t : Travel time (in hours)

In the case of the service time at a kerbside taxi stop, the minibus-taxis make their stops according to the following equations (adapted from Bian *et al* 2015):

$$T_s = T_d + T_m \qquad (6)$$

$$\begin{aligned} T_d &= C_d + \{pax \cdot H\} + t_{we} + t_{wl} \\ &= T\ + t_{we} + t_{wl} \end{aligned} \qquad (7)$$

$$T_m = t_e + t_l \qquad (8)$$

Where:
T : Minibus-taxi dwell time at stop
C_d : Time for opening and closing doors
T_s : Service time at the stop
T_d : Dwell time in and/or out of the stop
T_m : Time in which minibus-taxis move in and out of the stop
t_{we} : Time in which minibus-taxis wait to enter the stop
t_{wl} : Time in which minibus-taxis wait to leave the stop
t_e : Time in which minibus-taxis enter the stop
t_l : Time in which minibus-taxis leave the stop

The time spent, in hours, during acceleration and deceleration was calculated using the following equation:

$$T_a = 2 \times \frac{\left(\frac{V_f}{3.6}\right)}{\left(\frac{a}{3\,600}\right)} \qquad (9)$$

Where:
V_f : Final velocity (km/h)
a : Acceleration/deceleration rate (m/s^2)

For the queue-jumping lane and the single-lane pre-signal strategy, the minibus-taxis pick up and drop off passengers during the red phase of the traffic cycle. The waiting time during the red phase is therefore given by the average delay equations discussed above.

Finally, the travel time along the single 1-km corridor consists of the distance of the corridor divided by the speed.

To determine the monetary value of the user cost it is necessary to have a value of time to apply to each of the three main income groups: low, medium and high. Estimates of the value of travel time savings (VTTS) in South Africa vary; we decided to use typical values compiled by Hayes and Venter (2016) (Table 4). The percentage of each income group that makes use of cars and minibus-taxis respectively are from the National Household Travel Survey (Department of Transport/Statistics 2013).

The user cost is the total travel time multiplied by the value of time for each income bracket of the respective mode:

$$UC = TT \cdot VOT \cdot pax \qquad (10)$$

Operator cost

The operator cost consists of all the costs incurred whilst operating a vehicle. For the private vehicle, the running cost and maintenance cost were obtained from the Automobile Association of South Africa; these amounted to R3.74/km and R0.40/km respectively (Automobile Association 2013). For the minibus-taxi, little data is available on operator costs. We used typical values obtained from the Department of Transport's minibus-taxi operating cost model (Department of Transport 2008), adjusted for inflation using a rate of 4.5%.

Table 5 summarises all the input variables used in calculating the operating cost and briefly describes each.

The operator costs for minibus-taxis consist of the fuel cost, and the vehicle-time,

Table 6 Input variables used in calculating construction cost

Variable (unit)	Value
Cost of way (Rm/lane-km)	1.970
Land cost – CBD/Commercial (Rm/lane-km)	1.649
Land cost – Outer section (Rm/lane-km)	0.434
Minimum cost of station/stop (Rm)	0.4
Life of terminals (years)	20

Table 7 Total intersection capacity (veh/hr per direction)

Intersection intervention	East-West (mixed traffic)	East-West (minibus-taxis)	North-South (mixed traffic)
Kerbside taxi stop intersection	1 420	329*	580
Queue-jumping lane and the single-lane pre-signal strategy intersections	1 420	347*	450
Dedicated taxi lane intersection	2 840	1 420*	580
* Values are a fraction of the total mixed traffic values			

Table 8 Monthly savings per minibus-taxi with each infrastructure form compared to the kerbside stop (5-km route with priority intersections at 500 m spacings)

Infrastructure	Hourly operating cost	Operating cost savings/taxi	Minimum monthly savings/taxi	Maximum monthly savings/taxi
Kerbside taxi stop	R133	–	–	–
Queue-jumping lane	R105	R28	R1 232	R4 928
Single-lane pre-signal strategy	R108	R25	R1 100	R4 400
Dedicated taxi lane	R82	R51	R2 244	R8 976

vehicle-distance, and vehicle-fleet costs, as given by the following equation:

$$OC_t = \left(\frac{VH_c}{VH} \cdot h\right) + \left(\frac{VD_c}{VD} \cdot x\right) + \left(\frac{VF_c}{VH} \cdot h\right) + F_c \cdot \left(\frac{f_i^t}{h_i} + (f_c^t \cdot x)\right) \tag{11}$$

Where:

$$VH_c = V_s + V_m \cdot 0.5 \tag{12}$$

$$VD_c = V_t + V_m \cdot 0.5 \tag{13}$$

$$VF_c = V_f + V_a + V_c \tag{14}$$

Where:

VH_c : Vehicle-time cost, the total time-dependent cost for a minibus-taxi
h : Time spent, in hours, to travel along the corridor
VD_c : Vehicle-distance cost, the total distance-dependent cost for a minibus-taxi
x : Length of the corridor, measured in kilometres
VF_c : Vehicle-fleet cost, the total fleet-dependent cost for a minibus-taxi; a fleet-size of 1 was considered as the operation costs of a minibus-taxi were given per single vehicle
f_i^t : Idling component of fuel consumption for minibus-taxis
f_c^t : Idling component of fuel consumption for cars
h_i : Time spent, in hours, due to idling

A 50/50-split was assumed when apportioning vehicle maintenance cost according to vehicle-hours and vehicle-distance, as both variables affect the maintenance costs. Vehicle fuel costs were calculated in the same manner for both types of vehicles.

Construction cost

The construction costs were used to determine the capital costs of each form of infrastucture. The unit values listed by Del Mistro and Aucamp (2000), and adjusted for inflation, are summarised in Table 6. They apply to all infrastructure types except the single-lane pre-signal strategy which has no construction costs, as an existing section of road would be utilised for its purpose.

MODEL OUTPUTS

Intersection capacity

The capacities of the intersection for each intervention are summarised in Table 7. The capacity of the main corridor (east-west) is significantly higher than that of the cross street (north-south), in line with the model assumptions. The dedicated taxi lane allows for a greater traffic flow for both mixed traffic and minibus taxis.

To give a sense of the potential cumulative benefit of the operating cost savings to minibus-taxi operators, the savings were estimated for a notional 5-km route with priority intersections spaced at 500-m intervals. Considering a minibus-taxi operator working 8 hours a day for 22 days in a month (thus 176 hours per month), an upper limit to the savings is obtained. If it is assumed that the benefits accrue only during the morning and evening peak hours (thus 44 hours per month), a lower limit is obtained (Table 8).

The estimates show that a notional minibus-taxi operator may save between R1 100 and R9 000 when using the priority infrastructure on a single idealised route over the course of a month. These translate into potential savings of between 19% and 38% of taxi operating costs. This makes a strong case for the implementation of these infrastructure forms on busy corridors, as a way of delivering cost savings to operators. If these savings are passed on to passengers through fare reductions, passengers would also reap monetary benefits. An additional benefit to operators is that of higher vehicle productivity due to shorter cycles. These benefits can translate into higher revenue (assuming there is an unserved passenger demand), or lower fleet sizes.

Total cost

The total cost takes the user costs, operating costs and construction costs into account. The construction cost is only applied to the minibus-taxis. There is a reduction of up to 30% in total cost per one-way taxi trip when the kerbside taxi stop is compared to the priority infrastructure forms. The dedicated taxi lane has the lowest cost per trip at R32.78, followed by the queue-jumping lane at R40.81. The cost per trip for a private vehicle amounts to R7.09, which is significantly less costly than the minibus-taxi.

Figure 15 (p 64) shows the total costs expressed on a per-passenger basis. As expected, due to their higher occupancy, minibus-taxis transport passengers at significantly lower average cost to society than private cars. More importantly, the overall costs for the priority infrastructure cases are between 12% and 30% lower than for the base case, indicating that the estimated additional infrastructure costs of constructing priority facilities at intersections are more than off-set by savings in

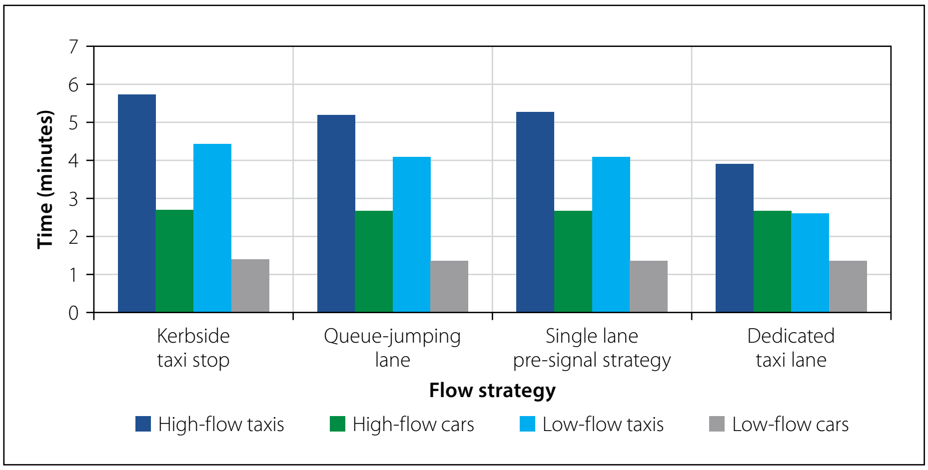

Figure 12 Travel time comparison between minibus-taxis and private vehicles

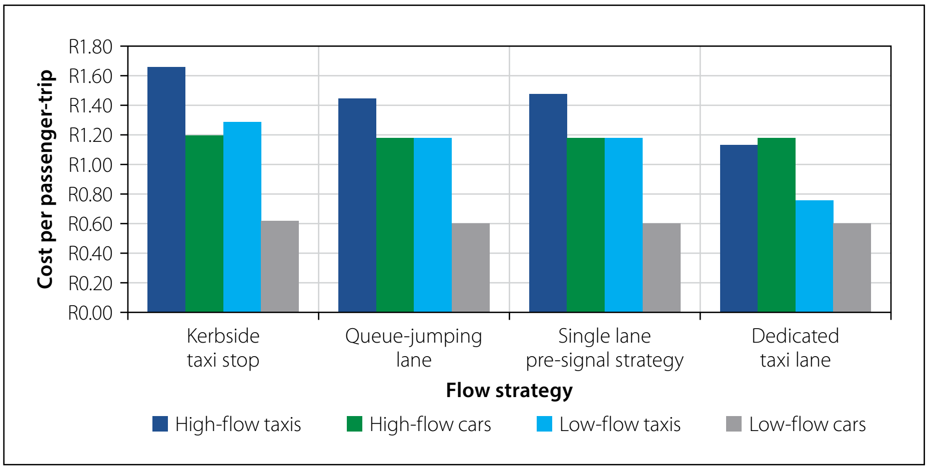

Figure 13 User cost per passenger per trip comparison between minibus-taxis and private vehicles

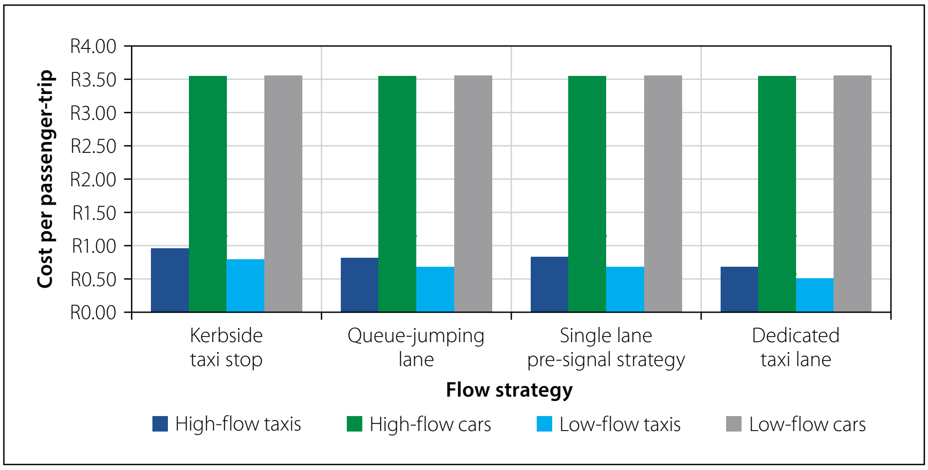

Figure 14 Operating cost per passenger-trip comparison between minibus-taxis and private vehicles

operating costs and travel time for taxi passengers, without significantly raising costs for private vehicles. Once again, a dedicated taxi lane has the lowest overall cost due to its significant time savings.

Travel time

Travel time is a primary component of user costs. The travel time for travelling along a notional 1-km corridor with one intersection that includes the stopping time at the intersection, as well as acceleration and deceleration time by either minibus-taxi or private vehicle, is illustrated in Figure 12.

As expected, for all treatments, travel times for the low-flow case are always lower than for the high-flow case due to lower queue delay. For the base (current) case, as well as all three forms of priority interventions, taxis experience more delay than cars due to the assumed far-side stop after clearing the intersection. All three interventions, however, see a reduction in travel time varying between 0.5 minutes for the queue-jumping lane and single-lane pre-signal strategy (a 9% reduction in travel time) and 1.8 minutes for the dedicated taxi lane (amounting to a 32% reduction). The time savings for the queue-jumping lane and single-lane pre-signal strategy are attributable to the priority green phase that reduces minibus-taxi queuing time, as well as the use of the red time for passenger boarding and alighting whereas the dedicated taxi lane's time savings are due to a reduction in queue lengths causing less congestion.

Private vehicles do not experience an increase in travel time when moving from the kerbside stop to any of the public transport infrastructure forms. This is due to the priority green time afforded to the minibus taxis being taken from the undersaturated opposite travel direction (i.e. north-south).

Cost outputs

The main outputs of this study relate to costs, and include user cost, operating cost, and total cost per passenger-trip. Construction cost was not shown as a cost, because, when reduced to a passenger-trip cost, it was not very significant.

User cost

The hourly user cost results are expressed on a per passenger-trip basis by dividing the total hourly user cost by the number of traffic arrivals per hour and the vehicle occupancy. Figure 13 illustrates these results.

A few observations are pertinent. Firstly, user costs rise for high-flow cases compared to low-flow cases, due to the extra queuing delay at the intersection. Secondly, only for the dedicated taxi lane, minibus-taxi user costs are lower than those of private vehicle users (by R0.05 per passenger-trip). The difference in minibus taxi and car per person-trip cost, however, becomes more significant when the priority interventions are implemented, differing by R0.26 and R0.30 for the queue-jumping lane and single-lane pre-signal strategy respectively. Thirdly, car user costs hardly change when implementing priority features for public transport, in line with the study objectives. Lastly, and most importantly, taxi user costs decline significantly (between 11% and 32%) with the priority treatments, reflecting the delay saving accruing to taxi passengers.

Operator cost

The operating cost per passenger-trip for minibus-taxis and private vehicles is illustrated in Figure 14. Per-person car costs are much higher than those of a taxi trip, largely due to the lower occupancy of the private car.

The minibus-taxi operating cost sees a 29% decrease when the kerbside stop is compared to the dedicated taxi lane, and a 15% and 14% decrease when it is compared to the queue-jumping lane and single-lane pre-signal strategy, respectively. This is largely driven by the reduction in travel time. The per person-trip costs of cars remain the same due to the travel times that do not vary.

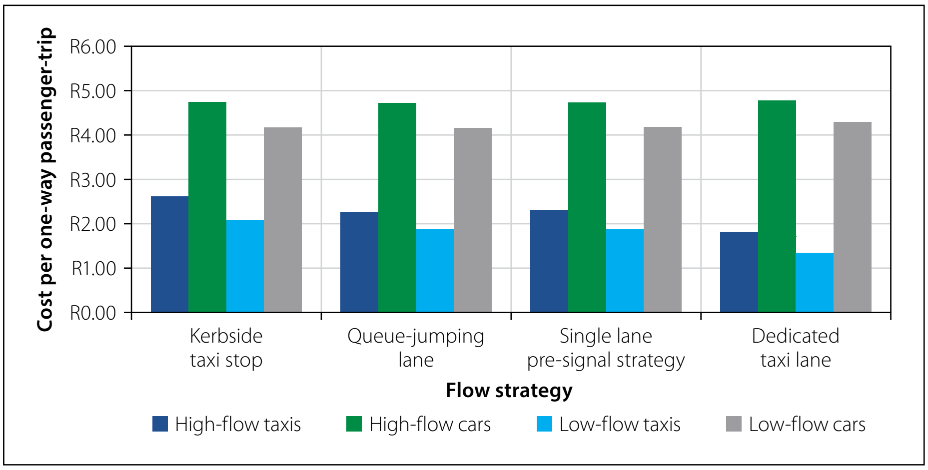

Figure 15 Total cost per passenger per trip comparison between minibus-taxis and private vehicles

Sensitivity analysis

A sensitivity analysis was carried out to check the robustness of the analysis against variations in key input variables. These variables included the length of the corridor, the ratio of minibus-taxi occupancy to private vehicle occupancy, passenger handling time for minibus-taxis, percentage of minibus-taxis stopping to pick up or drop off passengers, and the minibus-taxi vehicle hours travelled in a month. The results from the analysis are summarised in Table 9. The values in the table indicate the change when the base input value is compared to the upper limit value using total cost per passenger-trip as the value being compared.

Corridor length (while keeping the number of priority intersections constant), as well as the percentage of minibus taxis stopping to pick up or drop off passengers, had the largest impact on the output. In the case of corridor length, it implies a longer travel distance between priority intersections. Longer corridors reduced the comparative advantage of the queue-jumping lane and single-lane pre-signal strategy, but most significantly, the dedicated taxi lane, as their time savings become less significant relative to total operating costs. In the case of percentage minibus taxis stopping: the greater the percentage minibus taxis required to stop, the less beneficial the priority intersections become, and a lower net benefit is provided to the operators. The results are thus consistent with the outputs delivered by the model and do not cause the relative ranking of the treatments to change.

CONCLUSIONS

The kerbside stop is favoured by local authorities in South Africa as a first step towards regularising taxi operations and reducing delay to other vehicles. However, the net benefits can be substantially increased by modest additions of dedicated infrastructure at busy intersections. The paper contends that such repurposing of scarce road space may do much to promote public transport, especially the minibus-taxi which is the primary form of public transport in many developing countries. Judicious investment in priority infrastructure may be a very cost-effective way to raise the overall efficiency of the transport system, without significantly deteriorating conditions for other road users such as private car drivers and freight operators. Such investments will provide what amounts to an implicit operational subsidy to the paratransit sector since they reduce operator costs and delay. If some of these cost savings are passed on to passengers, they will benefit not only through faster and more reliable travel times, but also lower fares.

We developed simple analytical models to estimate the net economic impacts on taxi operators, passengers and private car users of three alternative priority measures – queue jumping lanes, single-lane pre-signal strategies, and dedicated taxi lanes. The models take typical driving and traffic conditions into account. The analysis was limited to undersaturated corridors with medium traffic volumes, on the assumption that higher volume corridors may be more suitable for larger interventions involving bus lanes and larger vehicles. The models may be useful to examine priority interventions in real-world cases, before detailed design or microsimulation efforts are undertaken.

The models were applied to a notional corridor to estimate the quantum of impacts under low and medium volume scenarios. The results showed that, compared to the kerbside taxi stop, priority interventions can reduce travel time by between 9% and 32%, and overall user cost (including fuel consumption) by between 11% and 32%. Over the course of a month, operators may save between R1 100 and R9 000 in direct operating costs, depending on fluctuations in delay conditions over the course of the day. Faster travel times may also reduce route cycle times and raise the vehicle productivity of minibus-taxi fleet operators. Taking construction costs into account, the net benefits are still positive, with the dedicated taxi lane outperforming the other two priority interventions due to shorter queues at intersections leading to shorter waiting times. Comparing the queue-jumping lane

Table 9 Sensitivity analysis outputs

Variable (varied)	Infrastructure form			
	Kerbside taxi stop	Queue-jumping lane	Single-lane pre-signal strategy	Dedicated taxi lane
Corridor length (1 – 9 km)	4.4	4.8	4.7	6.0
Ratio of minibus-taxi to private vehicle occupancy (2:5 to 18:1)	2.6	2.4	2.5	1.9
Passenger handling time (2 – 12 sec)	2.0	1.9	2.0	1.5
Percentage of minibus-taxis stopping (0 – 100%)	3.2	7.3	6.8	1.9
Minibus-taxi vehicle hours (40 – 360 hours)	0.43	0.42	0.42	0.44

and the single-lane pre-signal strategy, given their very similar benefits, the queue-jumping lane appears to be more promising as it is easier to implement and avoids many of the potential safety and operational issues that may arise with counter-flow pre-signal alternatives. These issues were not studied in detail and are perhaps worth further investigation in cases where the space for queue-jumping lanes does not exist.

This work was exploratory and raises many further questions regarding the planning and design of priority facilities for minibus taxi services in South Africa. The analysis needs to be extended to more congested and oversaturated traffic conditions to see where the limits of their economic feasibility lie. The assumptions regarding low cross-traffic volumes need to be relaxed to consider more variable delay conditions. Further analysis is also needed to investigate more realistic cases of traffic conditions that fluctuate across the day, and how this might affect the performance of the alternative treatments. Much further work is required on the design of priority treatments, including signalisation of queue-jumping lanes, geometric layout and signage, and passenger loading/unloading facilities. Behavioural aspects such as the stopping behaviour of minibus taxi drivers need to be added, especially since the traffic observations presented at the beginning of the paper showed that drivers already habitually display adaptations of priority lane driving behaviour, albeit illegal; behavioural shifts and better traffic law enforcement might need to be achieved to make these strategies work well. Lastly, we did not consider priority treatments involving purely signal priority and pre-emption strategies; these might also be worth investigation.

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REFERENCES

Automobile Association 2013. *Calculating the operating cost of a vehicle.* Automobile Association of South Africa. **https://www.scribd.com/document/128854202/Calculating-the-Operating-Cost-of-a-Vehicle-The-AA-of-South-Africa**.

Automobile Association 2019. *Fuel pricing.* **https://www.aa.co.za/fuel-pricing** [Accessed 19 June 2019].

Ben-Dor, G, Ben-Elia, E & Benenson, I 2018. Assessing the impacts of dedicated bus lanes on urban traffic congestion and modal split with an agent-based model. *Procedia Computer Science*, 130: 824–829. doi: 10.1016/j.procs.2018.04.071.

Bhattacharyya, K, Maitra, B & Boltze, M 2019. Implementation of bus priority with queue jump lane and pre-signal at urban intersections with mixed traffic operations: Lessons learned? *Transportation Research Record,* 2673(3): 646–657.

Bian, B, Zhu, N, Ling, S & Ma, S 2015. Bus service time estimation model for a curbside bus stop. *Transportation Research, Part C. Emerging Technologies,* 57: 103–121.

Brasuell, J 2019. *Dedicated bus lanes beating congestion in Portland.* **https://www.planetizen.com/news/2019/12/107482-dedicated-bus-lanes-beating-congestion-portland** [Accessed 12 February 2020].

Del Mistro, R F & Aucamp, C A 2000. Development of a public transport cost model. *Proceedings,* 19th Annual Southern African Transport Conference, 17–20 July 2000, Pretoria.

Department of Transport 2008. *Taxi recapitalization viability model.* Pretoria: Department of Transport.

Department of Transport/Statistics South Africa 2013. *National Household Travel Survey 2013.* Statistical Release P0320. Pretoria: Statistics South Africa.

Glambrone, A & Acitelli, T 2019. *Dedicated bus lanes on H and I streets NW aim to speed up rush-hour service, starting June 3.* **https://dc.curbed.com/2019/5/3/18528013/dedicated-bus-lanes-washington-dc** [Accessed 12 February 2020].

Govender, R & Allopi, D 2007. Analysis of the scientific aspects related to minibus taxi collisions. *Proceedings*, 26th Southern African Transport Conference, 9–12 July 2007, Pretoria.

Gu, W, Cassidy, M J & Li, Y 2012. *Models of bus queueing at curbside stops.* Berkeley, CA: University of California at Berkeley, Center for Future Urban Transport.

Hager, K, Rauh, J & Rid, W 2015. Agent-based modeling of traffic behavior in growing metropolitan areas. *Transportation Research Procedia,* 10: 306–315.

Halifax Regional Municipality (Canada) 2018. *Transit priority measures.* **https://www.halifax.ca/transportation/halifax-transit/moving-forward-together/part-7-transit-priority-measures** [Accessed 30 October 2019].

Hayes, G & Venter, C 2016. Trip utility and the value of travel time savings (VTTS) for commuter trips: Critique and recent advances. *Proceedings*, 35th Southern African Transport Conference, 4–7 July 2016, Pretoria.

Ilgin Guler, S, Gayah, V V & Menendez, M 2015. Providing bus priority at signalized intersections with single-lane approaches. *Transportation Research Procedia,* 9: 225–245.

Jennings, G & Behrens, R 2017. *The case for investing in paratransits.* Cape Town: Volvo Research & Educational Foundations.

Neumann, A, Röder, D & Joubert, J W 2015. Toward a simulation of minibuses in South Africa. *Journal of Transport and Land Use,* 8(1): 137–154.

Salazar Ferro, P, Behrens, R & Wilkinson, P 2012. Hybrid urban transport systems in developing countries: Portents and prospects. *Research in Transport Economics,* 39: 121–132.

Schalekamp, H & Behrens, R 2010. Engaging paratransit on public transport reform initiatives in South Africa: A critique of policy and an investigation of appropriate engagement approaches. *Research in Transportation Economics,* 29(1): 371–378.

Schalekamp, H & Behrens, R 2013. Engaging the paratransit sector in Cape Town on public transport reform: Progress, process and risks. *Research in Transportation Economics,* 39(1): 185–190.

Schalekamp, H & Klopp, J M 2018. Beyond BRT: Innovations in minibus-taxi reform in South African cities. *Proceedings,* 37th Southern African Transport Conference, July 2018, Pretoria.

Stamos, I, Kitis, G, Basbas, S & Tzevelekis, I 2012. Evaluation of a high occupancy vehicle lane in central business district Thessaloniki. *Social and Behavioral Sciences*, 48: 1088–1096

Tirachini, A 2014. The economics and engineering of bus stops: Spacing, design and congestion. *Transportation Research Part A,* 59: 37–57.

Transportation Research Board 2013. *Transit Capacity and Quality of Service Manual,* 3rd ed. Washington, DC: National Academy of Sciences.

Zheng, Z, Rasouli, S & Timmermans, H 2020. Modeling taxi driver search behavior under uncertainty. *Travel Behaviour and Society,* 22: 207–2018.

Zhou, G & Gan, A 2009. Design of transit signal priority at signalized intersections with queue jumper lanes. *Journal of Public Transportation,* 12(4): 117–132.

Zlatkovic, M, Stevanovic, A & Reza, Z 2013. *Effects of queue jumpers and transit signal priority on Bus Rapid Transit.* TRB Paper 13-0483. Washington, DC: Transportation Research Board.