MODELLING THE IMPACT OF PRIORITY INFRASTRUCTURE ON THE PERFORMANCE OF MINIBUS-TAXI SERVICES IN SOUTHERN AFRICA

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ABSTRACT

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 identify interventions that would formalise this behaviour: a single lane pre-signal strategy, queue-jumping lane, and dedicated public transport lane. The paper's objective 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. The single lane pre-signal strategy and the queue-jumping lane saw a decrease in total hourly cost of 45% and 43% 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.

1. INTRODUCTION

Recent initiatives to overhaul South Africa's entire public transport systems, in an attempt to address the legitimate 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 lanes, public toilets, and office space (Schalekamp & Klopp, 2018). The use of dedicated road space, as well as dedicated and time-of-day-reserved public transport rights-of-way is scarce and, where implemented, poorly enforced. Qualitative studies regarding the response of the minibus-taxi industry to proposed changes and formalisation of the industry to be incorporated into the Bus Rapid Transit system has been well documented (Schalekamp & Behrens; 2010, 2013). Research pertaining to the driving behaviour of the vehicle operators, however, is limited. It was the endeavour of this research to quantify, using mathematical modelling in Excel, the benefits that minibus-taxi operators receive when they skip traffic queues during congested periods of the day. An analytical approach was developed for a single bi-directional corridor with intersections rather than simulating the behaviour at a network-wide level. Mathematical equations were developed from first principles to calculate the driving costs along the corridor. The impacts on safety, which could be a large economic cost, was not quantified.

2. OBJECTIVES OF THE PAPER

The objectives of the study are summarised as follows:

- To identify priority infrastructure alternatives from literature and to determine their suitability for improving operating conditions in the paratransit industry.
- To develop mathematical models to ascertain the benefits of various priority infrastructure measures under a range of operating and demand conditions.
- To quantify the high-level economic impact that selected priority infrastructure would have on the paratransit operators, the passengers, and other road users.

3. IDENTIFYING SUITABLE PRIORITY INFRASTRUCTURE

3.1 Curb-Side Bus Stop

The most basic form of infrastructure intervention is the construction of taxi bays. Although much provision has been made for bus stops, little attention has been paid to providing stopping facilities for taxis (Dempster, 2018).

Bus service times at a bus stop occupies 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 curb-side bus stop is frequent.

With regards to the bus stop design, bus size, and congestion, Tirachini (2014) states that buses have the lowest capacity at a bus stop component of a bus route and is therefore the first element subject to congestion.

3.2 Queue-Jumping Lane

A queue-jumping lane allows the proposed 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, they leave the queue and enter the queue jump lane. A priority signal, thereafter, allows them to get a head-start on the other traffic and merge into the general traffic lane.

Preferential treatments are needed for high-occupancy transit vehicles to improve their operations. Zlatkovic, et al. (2013) evaluated the individual and combined effects of a queue-jumping lane and transit signal priority on the performance of a BRT system. They found that for each case, namely, queue-jumping, transit signal priority, and a combination of the two, the BRT was offered significant benefits whereas certain impacts were imposed on vehicular traffic. The greatest benefit to the BRT was observed with the combination scenario: the BRT travel times were reduced by between 13 and 22%; there was a significant improvement of the progression of the BRT vehicles through the networks; a reduction in intersection delays and waiting time; a significant increase in speed of 22%; and the travel time, reliability, and headway adherence were better than the other two scenarios. Furthermore, it was found that the implementation of any of the three transit preferential treatments did not affect vehicular traffic negatively. In fact, in some cases small improvements of 2% in the reduction of travel times were observed. The network performance of the BRT vehicles was also improved in all the transit preferential treatments when compared to the base case, the greatest of which was observed in the combination of queue-jumping and transit signal priority scenario.

3.3 Queue-Bypass Lane

A queue-bypass lane is similar to the queue-jump lane in that it allows the transit vehicle to skip the queue but differs in how it merges into the general traffic lane: in a queue-jump lane the passengers board during the red traffic cycle and once the bus receives a green, it leaves before the other vehicles and merges with the general traffic lane before crossing the intersection. In a queue-bypass lane the bus departs at the intersection with the regular traffic, without a priority green. Passengers board on the far side of the intersection and the bus re-enters the general traffic but must wait for an appropriate gap length. The difference between the two forms of infrastructure is illustrated in Figure 1 (Cesme, et al., 2014).

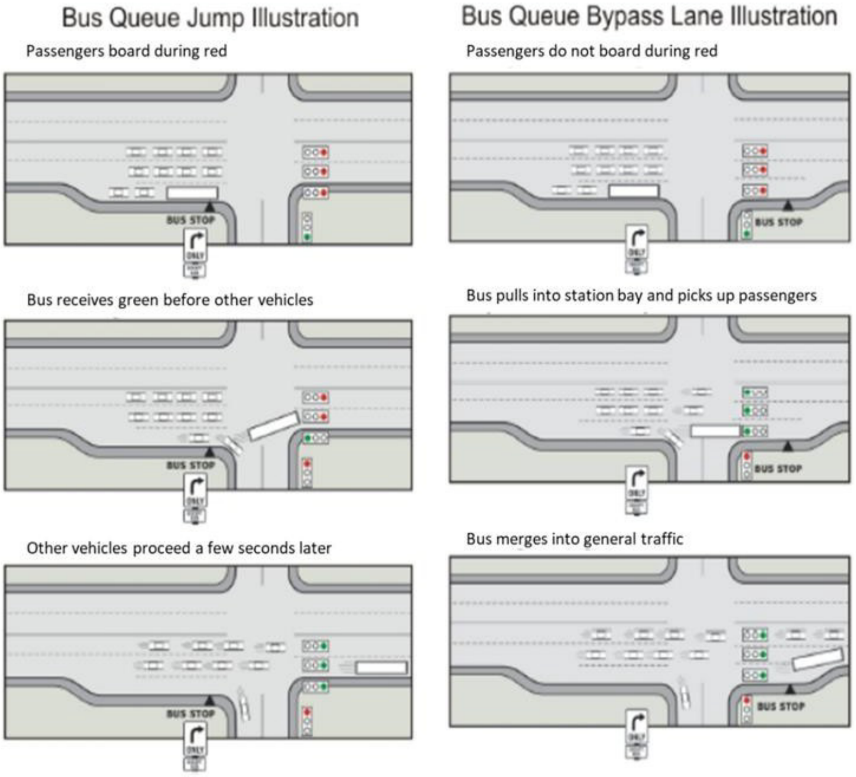

Figure 1: Queue jump and queue bypass lane (adapted from Cesme et al., 2014)

3.4 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 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 2 illustrates the setup.

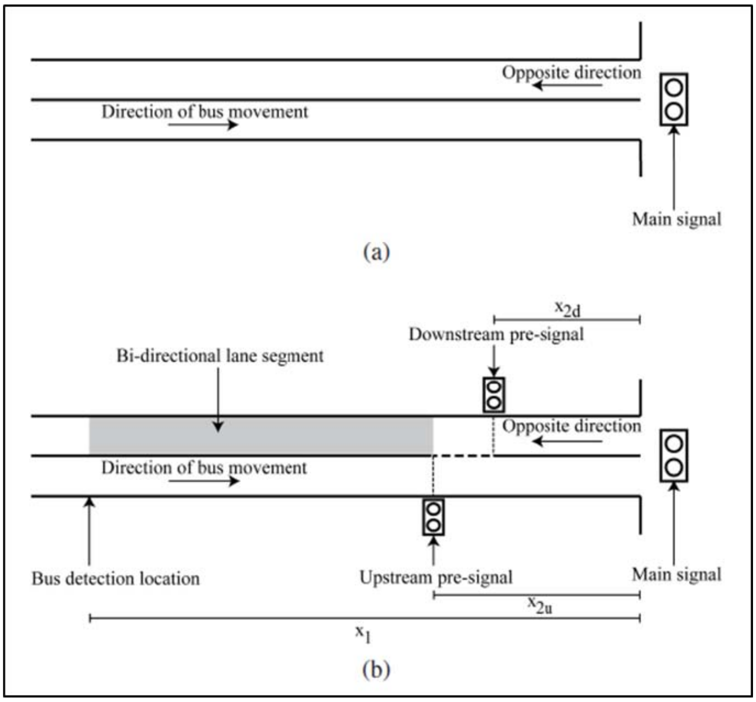

Figure 2: (a) Intersection with single lane approaches; (b) Pre-signal strategy (Ilgin Guler, et al., 2015)

3.5 Dedicated Bus Lane

A dedicated bus lane is a lane for buses that are separated from other traffic and are typically placed along the median, offset or in a physically separate lane (Planning Sustainable, 2019). They are indicated using pavement markings that restricts other vehicles from using them and can be used in conjunction with transit signal priority to improve the flow along a corridor. A high occupancy vehicle lane (HOV), by contrast, is a restricted traffic lane reserved exclusively for vehicles with a driver and one or more passengers.

Dedicated bus lanes are found to fundamentally improve the effectiveness of public transport when implemented at a city level. 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.

4. METHODOLOGY

Four forms of infrastructure were modelled, namely, a curb-side taxi stop, a queue-jumping lane, a single lane pre-signal strategy, and a dedicated taxi lane. The objective of the model was 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, which provides a balanced view.

This meant that the model would consist of four main sections which included:

1) The signalised intersection design which determined the cycle length, red phase length, and green phase length.

2) The user cost which entailed the time passengers in the minibus-taxis as well as private vehicle owners spent on the road.
3) The operating cost, which was based on time spent on the road as well as the distance covered and included 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.

This information in Table 1 provides the variables that are of importance to the user, to gain an understanding of the interface and subsequent results that are calculated by the model as part of the simulation process.

Table 1: Input variables used in the modelling process

Section	Variable
Signalised intersection design	• Average delay per vehicle (d_{avg}): $d_{avg} = \frac{r^2}{2C(1-{}^{v}/_{s})}$ (1) • Cycle length in seconds (⍰) • Arrival rate in vehicles per second (⍰) • Departure rate in vehicles per second (⍰)
User cost	• Vehicle capacity (⍰⍰⍰) • Passenger handling time (⍰) • Time for opening and closing doors (⍰⍰) • Acceleration and deceleration rate (⍰) • Final velocity (⍰⍰) • Income group value of time (⍰⍰⍰) - Low income (R4.00/hour) - Medium income (R18.00/hour) - High income (R31.00/hour)
Operator cost	• Vehicle operator salary (⍰⍰) • Tyres and other expendables (⍰⍰) • Vehicle maintenance (⍰⍰) • Facility maintenance (⍰⍰) • Administrative costs (⍰⍰) • Supervision and control centre (⍰⍰) • Fuel consumption for taxis and cars (f_c^t, f_c^c) • Fuel idling for taxis and cars (f_i^t, f_i^c) • Vehicle-hours (⍰⍰) • Vehicle-distance (⍰⍰)
Construction cost (del Mistro & Aucamp, 2000)	• Cost of way (1.045 Rm/lane-km) • Land cost – Residential (0.105 Rm/lane-km) • Minimum cost of station/stop (1 Rm) • Life of terminals (20 years)

Table 2 summarises the output variables used in each section of the model. The variables were subsequently used to perform the calculations pertaining to the cost per trip and total cost per hour of travel.

Table 2: Output variables generated by the model

Section	Variable
Signalised intersection design	• Effective red time in seconds: $r = \sqrt{d_{avg} \cdot 2C \cdot (1 - {}^{v}/_{s}}$ (2) • Effective green time in seconds $\boldsymbol{g = C - r}$ (3)
User cost	• Travel time in hours (⍰⍰) $TT = T_s + T_r + T_a + T_t$ (4) • Estimated service time (⍰⍰) (adapted from Bian et al., 2015) $T_s = T_d + T_m$ (5) $T_d = C_d + \{pax \cdot H\} + t_{we} + t_{wl}$ $= T + t_{we} + t_{wl}$ (6) $T_m = t_e + t_l$ (7) 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 bus 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 • Wait time at red (T_r) • Acceleration and deceleration time (T_a) $T_a = 2 \times \frac{\frac{Vf}{3.6}}{\frac{a}{3600}}$ (8) • User cost (⍰⍰) $UC = TT \cdot VOT \cdot pax$ (9)
Operator cost	• Fuel cost • Vehicle-time cost for taxis $VH_c = V_s + V_m \cdot 0.5$ (10) • Vehicle-distance cost for taxis $VD_c = V_t + V_m \cdot 0.5$ (11) *A 50/50-split was assumed when considering the vehicle maintenance cost as it relates to vehicle-hours cost and vehicle-distance cost

Table 2: Cont'd

Section	Variable
	• Vehicle-fleet cost for taxis $VF_c = V_f + V_a + V_c$ (12) • Running cost for cars** • Maintenance cost for cars** **The operating cost of cars was calculated using the values as provided by the Automobile Association where a vehicle running cost of R3.74/km and a vehicle maintenance cost of R0.40/km was used (Automobile Association, 2013). The fuel cost was calculated in the same manner as for the minibus-taxi • Operating cost for taxis and cars $OC_t = (\frac{VH_c}{VH} \cdot h) + (\frac{VD_c}{VD} \cdot x) + (\frac{VF_c}{VH} \cdot h) + F_c \cdot (\frac{f_i^t}{h_i} + (f_c^t \cdot x))$ (13) Where h is the time spent, in hours, to travel along the corridor and x is the distance of the corridor in kilometers.
Construction cost	• Construction cost per hour • Construction cost per one-way trip

Table 3 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.

Table 3: Arrival rate of private vehicles and minibus-taxis

Traffic flow rate	Private vehicle arrivals (veh/h)	Minibus-taxi arrivals (veh/h)
High flow rate	1090	350
Low flow rate	534	81

5. RESULTS

Travel time is a primary component of user costs. The travel time for travelling along a notional 1-kilometer 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 3.

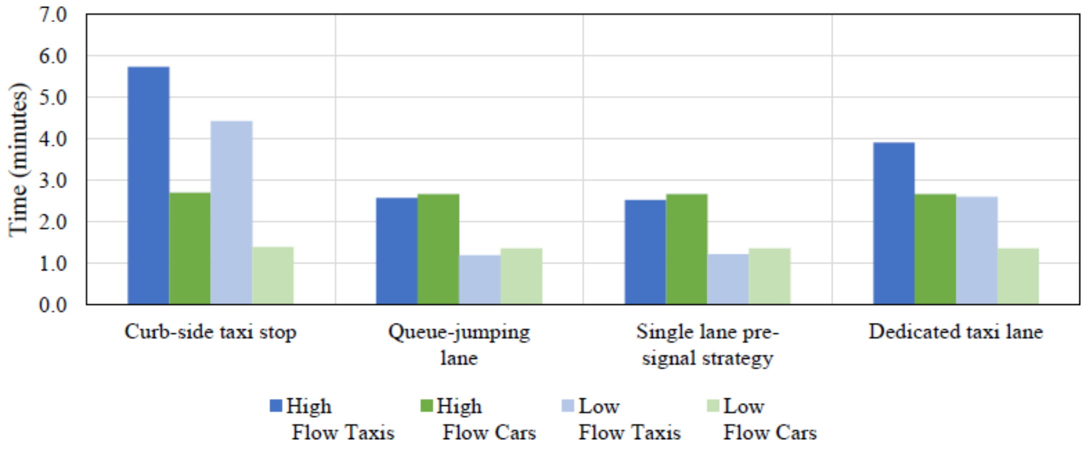

Figure 3: Travel time comparison between minibus-taxis and private vehicles

For the base (current) and dedicated taxi lane intersections, taxis experience more delay than cars due to the assumed far-side stop after clearing the intersection. By comparison, the queue-jumping lane and the single lane pre-signal strategy deliver a significant decrease in travel time of 3.2 minutes per trip (a 56% reduction). This is 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. The dedicated taxi lane sees a 32% or 1.8-minute reduction in travel time over the length of the corridor.

Private vehicles experience a 1% decrease in travel time when moving from the curb-side stop to any of the public transport infrastructure forms. This is due to the elimination of the delay that minibus-taxis cause when they decelerate to enter the curb-side bay, which does not apply to any of the other cases.

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 4 illustrates these results.

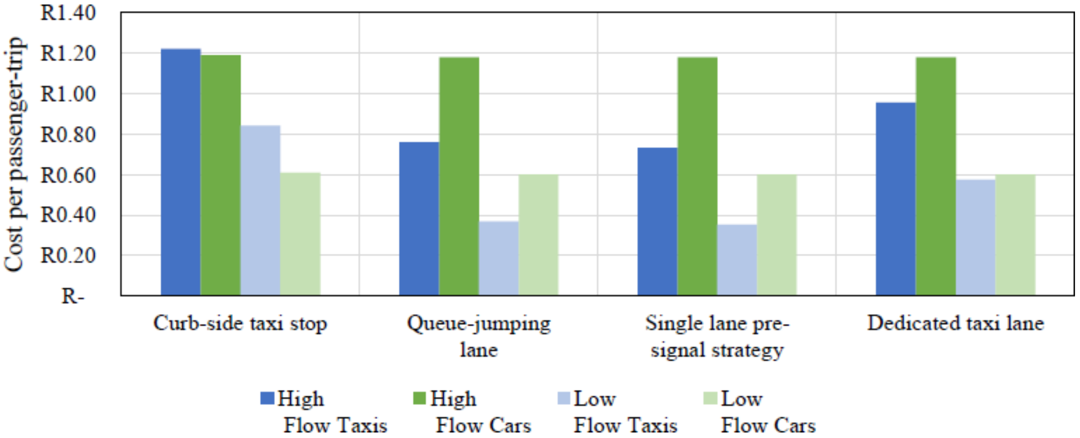

Figure 4: User cost per passenger per trip comparison between minibus-taxis and private vehicles

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, for all three infrastructure interventions, minibus-taxi user costs are lower than those of private vehicle users (by R0.42, R0.45, and R0.22 for the three treatments respectively). This is caused by a combination of two factors: delay reductions due to the priority given to public transport, and the lower value of time applied to taxi users as compared to car users. 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 with the priority treatments, reflecting the delay saving accruing to taxi passengers.

The operating cost per passenger-trip for minibus-taxis and private vehicles is illustrated in Figure 5. 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 50% decrease when the curb-side stop is compared to the queue-jumping lane, and a 49% and 29% decrease when it is compared to the single lane pre-signal strategy and the dedicated taxi lane strategies respectively. This is largely driven by the reduction in travel time and whilst the dedicated taxi lane should yield the lowest operating cost, this is not the case due to the relatively low minibus taxi flow rate.

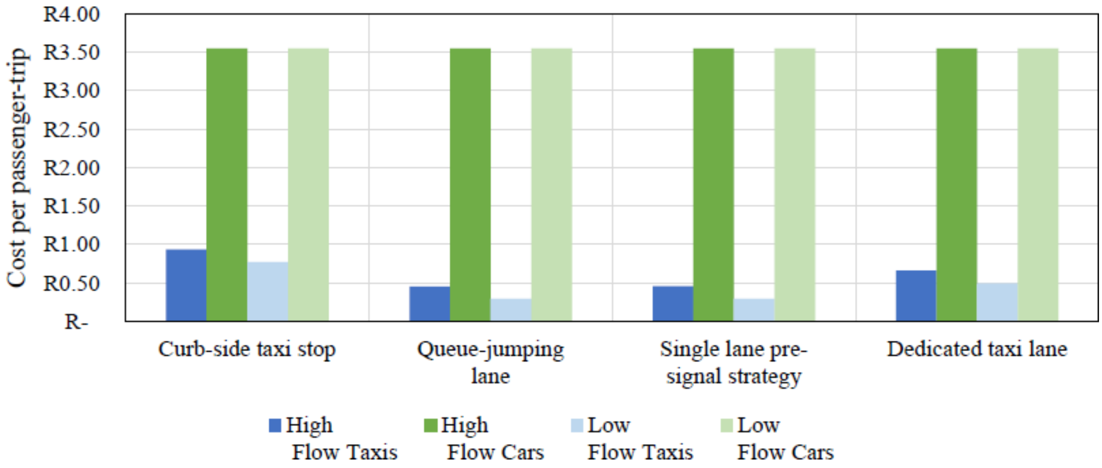

Figure 5: Operating cost per passenger-trip comparison between minibus-taxis and private vehicles

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-kilometer route with priority intersections spaced at 500-meter 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 4).

Table 4: Monthly savings per minibus-taxi with each infrastructure form compared to the curb-side stop (5-kilometer route with priority intersections at 500 m spacings)

Infrastructure	Hourly operating cost	Operating cost savings/taxi	Minimum monthly savings/taxi	Maximum monthly savings/taxi
Curb-side taxi stop	R266.113	-	-	-
Queue-bypass lane	R90.04	R176.29	R7 051.57	R31 026.90
Single lane pre-signal strategy	R85.99	R180.34	R7 213.76	R31 740.53
Dedicated taxi lane	R158.06	R108.27	R4 330.67	R19 054.97

The estimates show that a notional minibus-taxi operator may save between R19 054.97 and R31 740.53 when using the priority infrastructure on a single idealised route over the course of a month. These translate into potential savings of between 41% and 66% 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 cycle times – during peak periods minibus-taxis can make 54% more trips using the queue-jumping lane, 56% more trips using the single lane pre-signal strategy, and 32% more trips using the dedicated taxi lane. These benefits can translate into higher revenue (assuming there is an unserved passenger demand), or lower fleet sizes.

The total cost takes the user, operating, and construction costs into account. The construction cost is only applied to the minibus-taxis. There is up to a 54% reduction in total cost per one-way taxi trip when the curb-side taxi stop is compared to the priority infrastructure forms. The queue-jumping lane has the lowest cost per taxi trip at R22.51, followed by the single lane pre-signal strategy at R22.14. The cost per trip for a private vehicle amounts to R7.09 which is significantly less costly than the minibus-taxi.

Figure 6 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 25 and 45% 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 operating costs and travel time for taxi passengers, without significantly raising costs for private vehicles. Once again, the queue-jumping and single lane pre-signal strategies have the lowest overall cost due to their minimal infrastructure requirements.

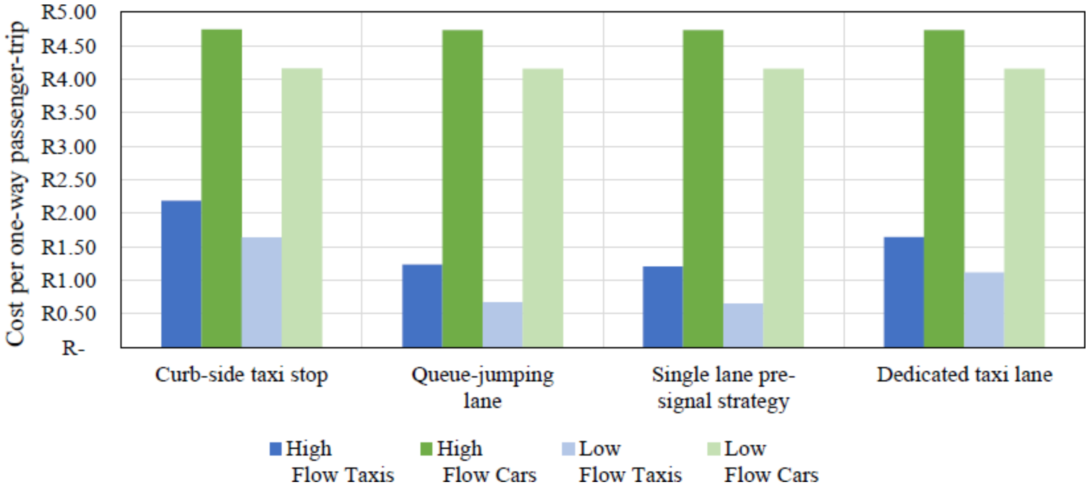

Figure 6: Total cost per passenger per-trip comparison between minibus-taxis and private vehicles

The total cost per hour takes the user, operating, and construction costs into account. The construction cost, however, is only applied to the cost for minibus taxis. In the CBD/commercial location during peak traffic there is a 54% reduction in total cost per one-way trip when the curb-side taxi stop is compared to the queue-jumping lane and single lane pre-signal strategy. In this traffic scenario the queue-jumping lane has the lowest cost per trip at R18.60, followed by the single lane pre-signal strategy at R18.80, the queue-bypass lane at R27.78, and the dedicated taxi lane at R30.80. The curb-side taxi stop is the costliest at R40.84 per trip. This trend in cost reduction is observed over all the different locations and peak or off-peak periods, although to different extents. The cost per trip for a private vehicle amounts to R7.07 which is significantly less costly than the minibus taxi. This cost, however, is not a truly indicative cost as it does not consider the number of passengers in the vehicle.

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 5. 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.

Table 5: Sensitivity analysis outputs

Variable (varied)	Infrastructure form Curb-side taxi stop	Queue-jumping lane	Single lane pre-signal strategy	Dedicated taxi lane
Corridor length (1 – 9 km)	4.5	8.5	8.5	6.1
Ratio of minibus-taxi to private vehicle occupancy (2:5 to 18:1)	4.6	2.5	2.5	3.4
Passenger handling time (2 – 12 sec)	2.0	1.0	1.0	1.5
Percentage of minibus-taxis stopping (0 – 100%)	3.1	1.0	1.0	1.9
Minibus-taxi vehicle hours (40 – 360 hours)	0.46	0.48	0.48	0.47

Corridor length (while keeping the number of priority intersections constant) had the largest impact on the output, as it implied a longer travel distance between priority intersections. Longer corridors reduced the comparative advantage of the queue-jumping lane and single lane pre-signal strategy most as their time savings become less significant relative to total operating costs. All other sensitivity tests enhanced the relative attractiveness of the queue-jumping and pre-signal strategies over the other two interventions. The results are thus consistent with the outputs delivered by the model and do not cause the relative ranking of the treatments to change.

6. CONCLUSIONS AND RECOMMENDATIONS

The curb-side 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 using the same curb space for other forms of public transport infrastructure at busy intersections.

The single lane pre-signal strategy and the queue-jumping lane proved to benefit the minibus-taxi operators as well as its passengers, allowing the driver to make more trips and reducing the time a passenger spends on the road. These two infrastructure forms can be implemented at busy intersections where there is no space to increase road capacity. The dedicated taxi lane also holds significant benefits but at a much greater financial cost. The location for a dedicated lane should be along a corridor that experiences a significant flow of minibus-taxis which will make it a more competitive alternative to the other two infrastructure forms. In none of the examined cases did the cost of car passengers change substantially because of the taxi treatment. Although this was built into the design of the treatments, it is important to note that it is possible to give substantial benefits to public transport users without necessarily degrading the LOS of car users.

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