MIXING THE FORMAL WITH THE INFORMAL IN SHARED RIGHT-OF-WAY SYSTEMS: A SIMULATION-BASED CASE STUDY IN TSHWANE, SOUTH AFRICA

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ABSTRACT

The study uses a microsimulation-based approach to examine the implications of mixing informal and formal operations in shared public transport lanes, based on a real-world Bus Rapid Transit service. The question is relevant to cities in the global south trying to transition towards upgrading informal paratransit services by investing in dedicated infrastructure, yet do not have sufficient demand to warrant exclusive Bus Rapid Transit systems. The key research question is whether excess capacity in bus lanes can be used to accommodate informal vehicles in a hybrid system, without substantially degrading the service offered to either bus or minibus passengers. The results indicate that under uncongested conditions, there is little benefit gained from hybrid operations. However, if congestion sets in during peak hours a clear case can be made for allowing taxis to share bus lanes under specific conditions. Both car users and public transport passengers benefit from up to a 50% reduction in travel time, with minimal impact on buses. These results persist even when taxi and bus volumes are increased to take account of modest demand growth and latent demand, although the rules of sharing infrastructure become critical. Policy implications for cities are discussed.

1 INTRODUCTION

As cities of the global south have struggled to cope with increasing urbanisation and motorisation, many have adopted Bus Rapid Transit (BRT) as a way of placing their urban transport on a more sustainable path (Hidalgo and Gutiérrez, 2013; Cervero, 2013). A considerable body of research has evolved around the implementation and impacts of BRT (Carrigan et al., 2014; Deng and Nelson, 2013; Hensher and Golob, 2008; Munoz and Paget-Seekins, 2015). One of the key insights that has emerged is that the outcomes of BRT-based development vary widely across locales, and not all are positive. Many studies have demonstrated significant benefits to BRT passengers in terms of savings in travel time and cost (Cervero, 2013; Venter et al., 2018), and to act as a catalyst for systemwide upgrading of public space (Wright and Montezuma, 2004) and urban mobility (Muñoz and Gschwender, 2008; Hidalgo et al., 2013). Many case studies have sought to understand the conditions under which BRT are successful, including land use, political, and financial (Kumar et al., 2011; Nikitas and Karlsson, 2015).

Yet a fair amount of critical work has also started to emerge examining the limits of BRT. Case studies of unsuccessful BRT systems (e.g. Bangkok, Delhi, and Indonesia (Guerra et al., 2020; Mallqui and Pojani, 2017; Wu and Pojani, 2016) have shed light on contributing factors, while some have questioned whether even exemplars like Bogota and Curitiba are really as successful as they seem (Duarte et al., 2011; Gilbert, 2008). One of the key features of 'unsuccessful' systems is their inability to attract sufficient ridership, leading to financial unsustainability, as the key justification for investing heavily in dedicated infrastructure – passenger density – is not met. This has been the case in South Africa, where despite having invested almost a billion dollars in BRT systems in five cities with operational BRT systems (Sunday Times, July 2017), ridership is still reported at about 120 000 to 150 000 people per day with an operating cost recovery of about 40% (Van Ryneveld, 2018)[1]. In the case of Johannesburg's BRT only 3% of public transport trips are made on it and the ridership figures (per bus) are one tenth that of more successful BRTs (Scorcia and Munoz-Raskin 2019). Reasons suggested for this include low population densities, continued competition from parallel public transport services, and the lack of network effects stemming from the limited reach of the BRT networks (Hook and Weinstock, 2021).

This has led to public views of the systems as flawed and "white elephants" (Mabena, 2017), while key decision makers have questioned the continued rollout of BRTs as financially unsustainable (Van Ryneveld, 2018).

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[1] These are pre-pandemic figures, that have now been reduced significantly by the effects of Covid-19.

Another factor that has contributed to the problematic perception of SA's BRTs is their relationship to the informal transport sector. From the start the South African government sought to use BRT as a way to formalise and transform the minibus-taxi industry. This industry is the dominant public transport mode in the country, transporting about two-thirds of all public transport trips with a fleet of about 150,000 minibuses (mostly 16-seater vehicles) (Department of Transport, 2007). BRT systems in Cape Town, Johannesburg, and Tshwane have succeeded in incorporating some previous minibus owners and drivers into new BRT operating companies, following the transformation model of Transmilenio (Venter, 2013). But progress has been much slower than expected (Manuel and Behrens, 2018), and it has become clear that formalising all minibus-taxis will be neither feasible nor affordable in the long run. Policy and scholarly attention has therefore turned to the question of how informal and formal services can effectively co-exist, and what policy trajectories would best deliver incremental improvements in the collective public transport system while trying to manage such a hybrid system on the ground (Salazar Ferro and Behrens, 2015; Salazar Ferro et al., 2013).

This paper aims to make a contribution to this question, by focusing on the shared use of bus lane infrastructure. The key research question is whether excess capacity in bus lanes can be used to accommodate informal vehicles in a hybrid system, without substantially degrading the service offered to either bus or minibus passengers. While it is acknowledged that service quality perceived and desired by passengers using these different modes might differ with regards to aspects such as crowdedness, fare, waiting times, and network extent, this study is restricted to traffic impacts. The impacts on external (car) traffic are also of concern. We take a case study approach, focusing on the actual operations on a section of a BRT corridor in Tshwane, South Africa, where both BRT buses and minibus-taxis operate. Several scenarios are specified representing alternative approaches to lane sharing, and performance in terms of passenger travel times, queue lengths, and Level of Service (LOS) is measured.

The research method uses a micro-simulation model which simulates the interactions between individual vehicles. This is a suitable approach since very little research has been done on the driving behaviour of minibus-taxis, making the application of theoretical or analytical traffic engineering models difficult. We thus pay attention to the calibration of the microsimulation model using in-field observations of taxi driving behaviour. The study delivers insights that are relevant not only to South African transport policy, but also to other countries in the global south struggling with questions of the co-existence of formal and informal public transport systems.

The article first reviews relevant literature on hybrid public transport systems and attempts to model them. Then follows descriptions of the case study area and model, followed by results and conclusions on the implications for public transport development in global south cities.

2 LITERATURE

2.1 Hybrid public transport operations

There is a growing literature on the informal public transport industry (also called paratransit, popular, or artisanal transport), based on an acknowledgment that these modes are fundamentally important for mobility in many global south cities (Behrens et al., 2015). The earlier literature discussed the problems of informal operations, including poor safety, environmental, and passenger comfort track records, and various ways of regulating or formalising them (e.g. Cervero and Golub, 2007; EMBARQ, 2014). However more recently much more focus has been put on gradual efforts at paratransit upgrading, leading to the idea of hybrid public transport systems where formal and informal systems co-exist even while incremental improvements are sought (Salazar Ferro et al., 2013). Most research on hybrid systems has focused on spatially segregated arrangements, for instance where informal operators serve a feeder role by ferrying passengers to/from the formal system, which might be a BRT or rail system (Del Mistro and Behrens, 2015; Plano et al., 2020). Salazar Ferro et al. (2012) identify other arrangements where informal systems might complement formal bus routes, such as connecting corridors, peak lopping, and shared busways (interlining). Yet no research has been found on the actual operational implications of such hybridity in real-life situations.

2.2 Simulation of taxi and bus operations

The modelling of traffic operations can be done in various ways, including analytical and simulation models. Simulation models use mathematic models applied to vehicles (across different modes) and their interaction with the road network in order to replicate and observe the random nature of real traffic. Simulation models can be implemented at different scales and levels of detail, ranging between agent-based and microsimulations. According to Bonabeau (2002) agent-based simulation can be defined as a system of autonomous decision-making entities called agents. Each agent assesses its situation individually and makes decisions based on a given set of rules defined by the modeller. Neumann et al. (2015) developed agent-based models for minibus-taxis in South Africa to simulate operators’ decisions around routing, frequencies, and fleet sizes at a city-wide level. Microsimulation models take the same approach but tend to simulate smaller areas at a finer scale, using detailed vehicle following and lane changing models to represent vehicle movement and interactions (Gao, 2008).

These models employ a psychophysical approach which defines decision making based on human perception (Aghabayk et al., 2010). The model requires a positive response to the following questions before a lane change can be considered: Is there a desire to change lanes, what is the driving situation in adjacent lanes, is the lane change possible? To answer these questions, the agent considers the driving speed in the current and adjacent lanes as well as the front to rear distance between vehicles.

Since microsimulation requires detailed information on vehicle and driver performance, it stands to reason that the differences between vehicle classes need to be known. Specifically, paratransit vehicles have potentially different vehicle specifications, driver behaviour and stopping behaviour. There is evidence, for instance, that minibus-taxi drivers drive more aggressively than other drivers (Sinclair and Imaniranzi, 2015), which would raise the need for adjusting parameters like minimum headways, acceleration and deceleration rates, and desired speeds from those used for private vehicles.

Unfortunately the number of studies that have sought to characterise these for informal or paratransit vehicles are relatively few. Cheng et al. (2014) investigated the capacity effect of heterogeneous vehicle behaviour (such as that of taxis) on a network. It was suggested that the physical vehicle performance (such as dimensions and mechanical performance) of taxis do not differ significantly from that of private vehicles. The difference comes in with driver behaviour: taxi drivers are indeed more aggressive and exhibit poor lane-adherence discipline and adherence to the standard rules of the road. The authors found that when taxis led a queue at a signalised intersection, the start-up lost time was reduced which improved the overall capacity of the intersection. A case study from Zimbabwe showed that although the capacity of an intersection increased with the presence of informal taxis, the overall network's vehicular delay rose (Dumba et al., 2016). This can be explained by taxis' pick-up and drop-off behaviour which is very erratic as well as the aggressive lane change behaviour which causes delays for private vehicles.

Bus rapid transit operations have been simulated more extensively. Yu et al. (2006) simulated BRT driving behaviour and validated the model by comparing their outputs to GPS data they collected. They then published suitable default values for simulating the movement of BRT buses. Widanapathiranage, Bunker and Bhaskar (2015) performed a microsimulation of bus stations in Brisbane, Australia using Aimsun, focusing on congestion caused by bus to bus interference when multiple buses make use of the same station.

Zhou et al. (2017) used VISSIM simulation software to study the optimisation of BRT performance by modifying traffic signal timing. The model included dedicated bus lanes and general lanes to test the effect of different volumes of general traffic at the entrance to dedicated BRT lanes, on BRT performance. The results indicated increased passenger delay and decreased BRT travel speeds as the volume of general traffic increased (despite the fact that buses operated in dedicated lanes). Mao and Bertini (2008) also used VISSIM to simulate a congested arterial road in Beijing, including general lanes, bus only lanes and pedestrian facilities. The model captured the interaction of buses, non-buses and pedestrians at locations where the infrastructure crossed.

In South Africa, Chitauka and Vanderschuren (2014) performed a microsimulation of two corridors in Cape Town, in order to determine if partial bus priority strategies could provide the same performance benefits that a full BRT could. While the simulation did not explicitly include minibus-taxis, it did show that reasonable simulation results can be obtained under local traffic conditions. Other work that successfully calibrated microsimulation models for South African traffic environments was undertaken by Jobanputra & Vanderschuren (2012).

2.3 Interaction between formal and informal vehicles

We have found no simulation studies that have examined the sharing of dedicated lanes between buses and smaller vehicles. There has been one attempt to model the effect of taxis' lane changes (from general to BRT lanes) on buses using a mathematical approach (Fowkes et al., 2014). The study was based on the theoretical Lighthill-Whitham continuum model and did not take into account stopping behaviour or intersections. Nevertheless, the study usefully demonstrated that the overall corridor throughput may improve by allowing the taxis to move from the general to BRT lanes, but that this only applies within a specific range of traffic densities.

3 CASE STUDY DESCRIPTION

3.1 Study area

Tshwane is a sprawling metropolitan municipality in South Africa’s Gauteng province, and includes Pretoria, the administrative capital of the country. It has a population of about 3 million people. The A Re Yeng Bus Rapid Transit system was implemented in December 2014 as a solution to growing congestion and to improve accessibility for outlying low-income areas to centrally located opportunities. The network consists of two trunk routes (9 and 7 km long) converging on the Central Business District (CBD), supported by 6 feeder routes connecting at key stations (Figure 1). Infrastructure consists of dedicated median bus lanes and 12 closed stations. It is important to note that the current routes are seen as first steps toward a more comprehensive city-wide BRT network comprising 11 routes and 69 km of trunk (City of Tshwane, 2015).

In line with national policy minibus-taxi operators on competing routes were corporatized and became operators of the BRT bus fleet. However, given the focus of the BRT on the city core, very few taxi routes were actually removed, as they mostly serve more distant origins and/or destinations. Most taxi routes are radial and converge on the CBD, where considerable congestion occurs during peak periods.

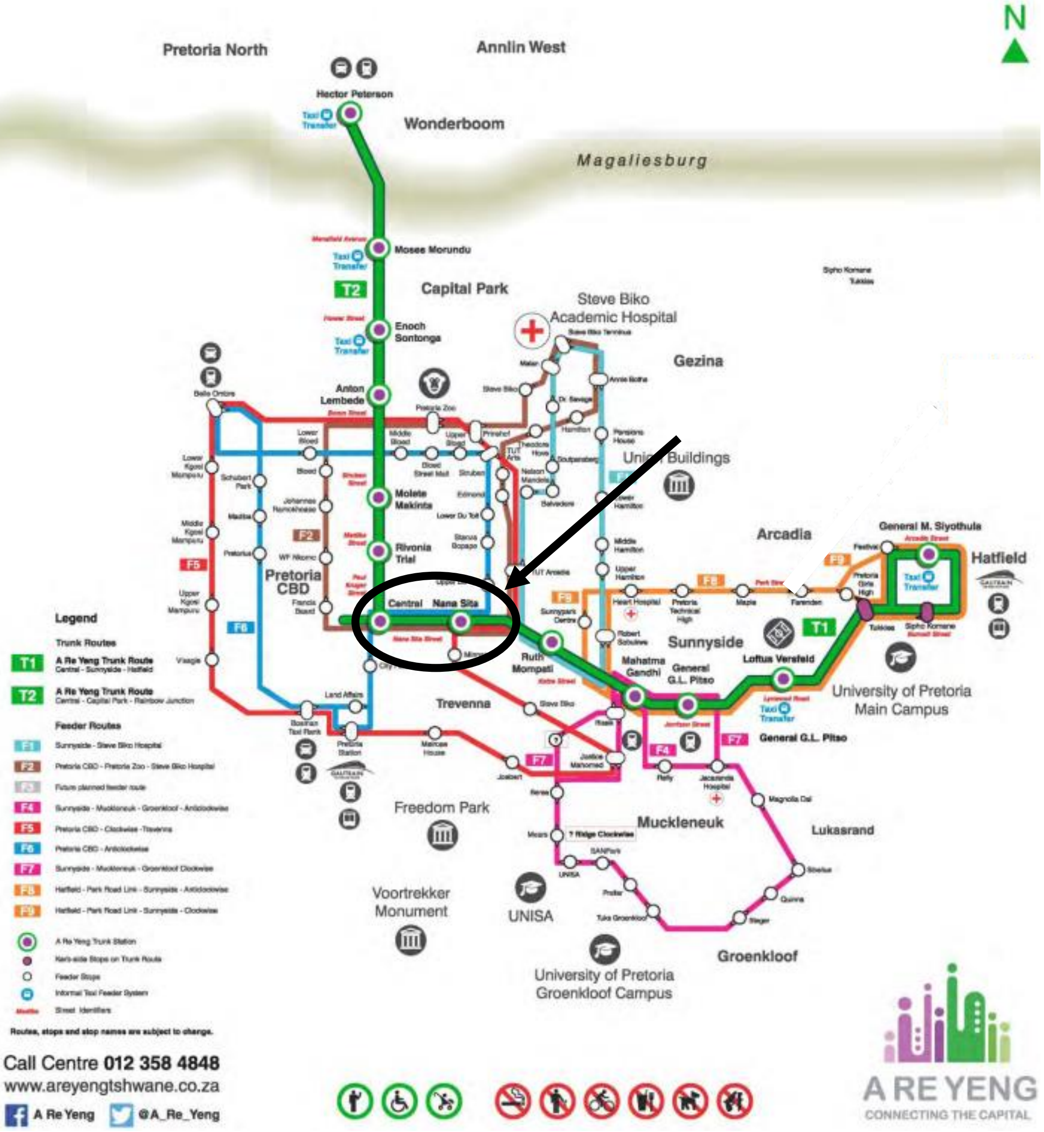

Figure 1: A Re Yeng BRT system map (City of Tshwane, 2015)

This study focuses on a section of the trunk for the T1 line within the CBD (Figure 2). The 1200 m-long section runs in the median of a busy corridor along Nana Sita Street. The street was substantially reconstructed during construction of the BRT infrastructure, now offering three lanes per direction for general traffic, plus a BRT lane and bypass lane at stations. The section includes 5 signal-controlled intersections and two BRT stations, both of which also serve feeder buses.

The section was chosen to exemplify some of the complexity of multimodal operations, including both general and bus lanes, multiple BRT stations, and multiple signalised intersections. In addition, there is both a large minibus taxi demand and private car congestion during peaks.

Figure 2: Primary study area (Source: City of Tshwane)

3.2 Vehicle types

BRT buses used on the trunk routes are either 12-meter standard buses or 18-meter articulated buses with passenger capacities of 60 and 90 passengers respectively. Minibus taxis are available in a variety of brands and sizes, but the majority are 5.4 meters long with a capacity of 16 passengers.

4 MODEL SETUP

4.1 Network configuration

The performance of the experimental section – current and hypothetical – is modelled using VISSIM software (PTV, 2018). A microsimulation package based on standard car following theory but flexible enough to be adapted to a variety of local conditions, VISSIM has been used successfully to model the interaction between private vehicles and buses in other studies (Mao and Bertini, 2008; Zhou et al., 2017). Appendix A contains key input parameters used in the simulation.

Detailed information about the network such as lane widths, platform lengths, and road markings were obtained directly from City of Tshwane. Other measurements were based on municipal imagery and on-site observations. No parallel roads were included, but five cross streets were modelled up to the next intersection to allow more queue build-up. Figure 3 shows a comparison between the model and aerial images of the study area.

Figure 3: 3D model comparison view

4.2 Data collection

Data collection on traffic patterns and behaviour consisted of video recordings at all intersections, GPS tracking of probe vehicles, and official bus timetables. Twelve-hour traffic counts were extracted from the video recordings, from which input traffic volumes (for private vehicles, heavy vehicles, and taxis) could be obtained for the simulations. Figure 4 shows that eastbound volumes are consistently higher than westbound volumes, indicating that motorists use alternative routes in the westbound direction. Traffic signals along the corridor favour eastbound traffic, causing westbound to display much more congestion even at lower volumes. Typical for a CBD-type location, off-peak flows are generally high, although the AM (07:00 to 08:00) and PM peaks (15:15 to 16:15) are discernible.

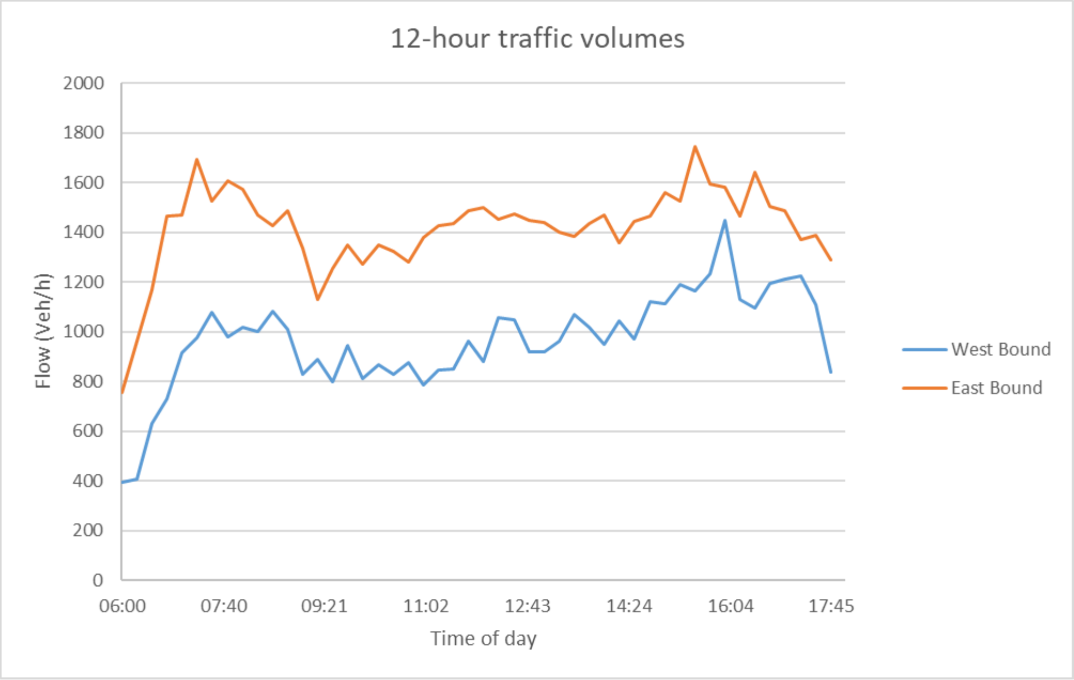

Figure 4: 12-hour traffic volumes through Lilian Ngoyi intersection

The simulation covered a typical 12-hour weekday between 6:00 and 18:00 to include both peaks. Because the simulation is a random process the simulation must be repeated to capture the variation in output data. Each simulation run was repeated 10 times with different random seeds.

The video footage was also used to determine queue lengths, vehicle adherence to regulations, parking times, dwell times of buses at BRT stations, taxi dwell times, saturation flow rates, and traffic signal timing and phasing. Observed BRT bus frequencies corresponded with the official timetables and varied between 2 and 9 buses per hour per direction during the day. Taxi frequencies varied between 12 and 94 taxis per hour per direction during the day. In terms of passenger volumes taxis transport in the order of 1100 pax/hr/direction during peak periods while BRT buses transport in the order of 300 pax/hr/direction. These figures are low when compared to international BRT systems which often operate at full passenger capacity during peak periods, and indicate that considerable excess capacity currently exists in the buslane. The amount of excess capacity could be estimated by referring either to the capacity of the bus stations (which depends on the maximum saturation levels allowed to avoid buses blocking each other), or the capacity of the lanes between stations (ITDP, 2017; Widanapathiranage et al., 2015). Taking both into account, we estimated the buslanes can accommodate an additional 87 buses per hour or 334 taxis per hour before service deteriorates to unacceptable levels, meaning that the current system operates at between 4% and 10% of capacity. The detail are in Appendix B.

The taxi association operating in the study area terminates its routes beyond the experimental section. Thus, no routes start or end along the corridor, so there is no holding of taxis to have to model. Due to the proximity of terminals there are very few passenger collections and drop-offs in the study area; those that do occur generally take place at signalised intersections during the red phase, causing little vehicle delay. This means that the stopping of taxis for passenger boarding or alighting did not need to be modelled explicitly – making this a somewhat simpler case than what is found in most other paratransit corridors. Some routes do not travel the entire section but enter or leave it to serve other points away from the terminals.

4.3 Calibration for minibus-taxi driver behaviour

A critical calibration parameter for VISSIM is the desired travel speeds and acceleration and deceleration rates of various vehicle classes. Since little work has been done on calibrating the behaviour of especially informal public transport, this data had to be collected locally to ensure a realistic model could be set up. Hand-held GPS tracking devices recorded the location and speed of a sample of minibus-taxi (approximately 30km on 3 taxis) and bus (approximately 30km on 4 buses) trips during the peak as well as off peak periods. Microsimulation models vehicle speeds endogenously in response to interactions with other vehicles, geometric and control conditions, but requires desired (or maximum) speeds on different sections. These were extracted from the off-peak observations (i.e. under uncongested conditions), while peak-period data was used for model validation. Average desired speeds were measured on Nana Sita Drive. The buses had the lowest desired speed of 42.0 km/h, private vehicles had a desired speed of 45.2 km/h and taxis had the highest average speed of 50.2 km/h.

The second calibration parameter, the desired acceleration and deceleration rates for passenger vehicles, BRT buses and taxis, was also extracted from the GPS data. It is important to calibrate this correctly as minibus-taxi drivers are thought to display more aggressive driving behaviour than other drivers (Sinclair and Imaniranzi, 2015), so standard parameters would not apply. VISSIM requires the upper bound, mean and lower bound acceleration/deceleration rate at different speeds. The measured values show that taxis' acceleration rates are similar to those of buses, and lower than private vehicles', probably reflecting differences in gross weights (Figure 5). However, taxis display higher average deceleration rates, especially at higher speeds (Figure 6), signifying harder braking behaviour.

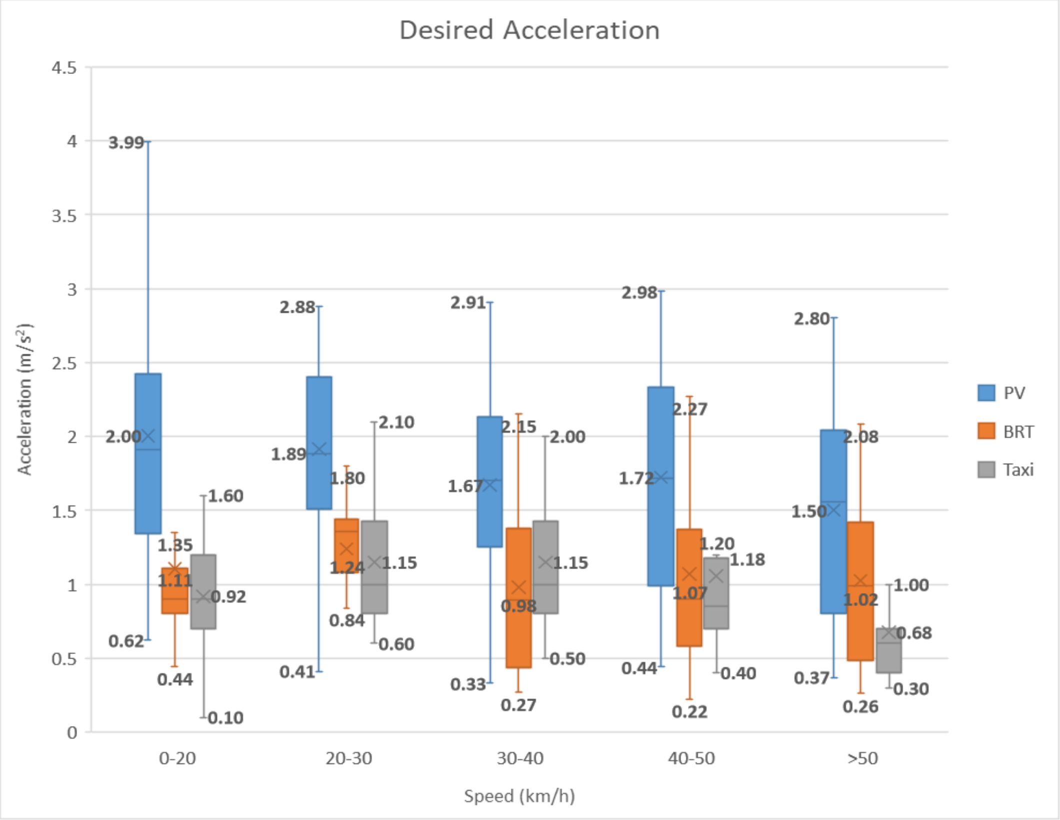

Figure 5: Desired acceleration observed from GPS tracks of probe vehicles (PV = private vehicles)

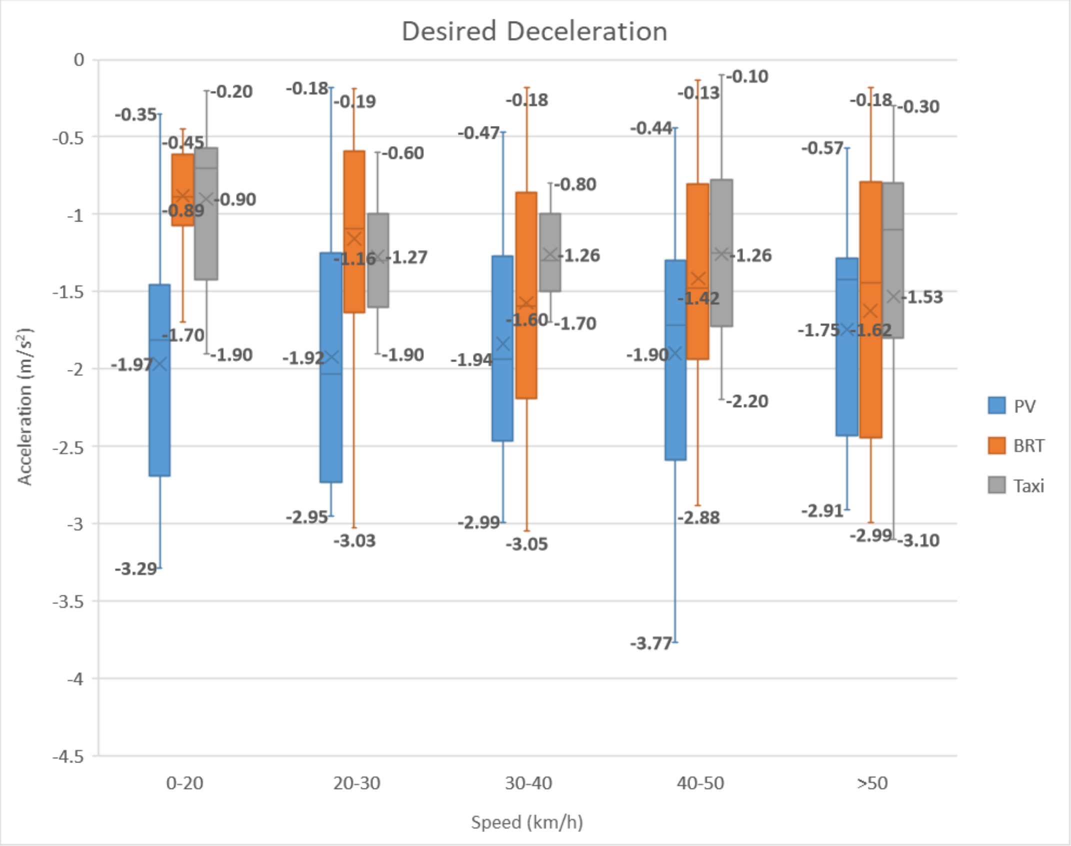

Figure 6: Desired deceleration observed from GPS tracks of probe vehicles

Specification of the network, saturation flow rates, and traffic signal operations was further fine-tuned to ensure simulated peak hour queue lengths matched observed queues to within accepted tolerance levels using the standard Geoffrey E. Havers (GEH) statistic. This statistic is commonly used to calibrate microsimulation models (Kabashkin et al., 2017) as a function of the modelled and observed traffic flows and is calculated as follows:

$$GEH = \sqrt{\frac{2(M-C)^2}{M+C}}$$

Where:

M= Modelled hourly traffic volume

C= Counted hourly traffic volume

4.4 Validation

The model was validated by comparing observed and modelled travel times along the whole section for two hourly periods during the morning peak period. Table 1 shows the results, together with the GEH statistic.

Table 1: Travel time validation results (in seconds)

	Eastbound general			Westbound general			Eastbound BRT			Westbound BRT		
Time	Observed	Modelled	GEH	Observed	Modelled	GEH	Observed	Modelled	GEH	Observed	Modelled	GEH
06:00-07:00 AM	136.1	147.5	0.96	250.4	246.7	0.23	238.9	228.1	0.71	267.1	269.7	0.16
07:00-08:00 AM	120.2	150.9	2.64	289.3	320.7	1.80	275.6	232.5	2.7	224.9	279.8	3.46

The GEH values calculated are all well below 4 which is usually accepted as the upper limit for a validated model Kabashkin et al. (2017).

4.5 Scenarios

Four scenarios were specified for simulation, to represent a range of approaches toward hybrid operations:

4.5.1 Scenario 1 (Benchmark)

The 2019 base model representing the current situation was used as the benchmark scenario. Taxis and private vehicles travel in general lanes and buses travel in BRT lanes.

4.5.2 Scenario 2 (Remove)

In this scenario all minibus-taxis are removed from the network. This corresponds with the current long-term strategy of the municipality, which intends for formal BRT to completely replace informal modes. It is assumed that the number of public transport users remains constant and that all taxi passengers shift to the BRT buses. The result was that BRT frequencies had to increase by 285% (from 5 to 13 buses per hour on average) to accommodate the 1004 passengers per hour displaced from taxis, taking the different vehicle sizes into account). In comparison with the benchmark, scenario 2 indicates the incremental traffic impact that the minibus-taxis have on traffic conditions.

4.5.3 Scenario 3 (Shift)

Minibus-taxis are forced to share the dedicated BRT lanes and use them as express lanes, although they may enter and leave the lanes at intersections for turning movements where taxi routes only partly overlap with the experimental section. No minibus-taxis are permitted in the general lanes. This scenario is meant to test a forceful approach that maximises the use of the bus lane infrastructure, by establishing what amounts to two parallel systems with complete separation between private and public transport within the corridor. While practical implementation of this scenario may be difficult due to its need to strictly enforce the separation, it is of interest from a theoretical viewpoint. For the purposes of the simulation it was assumed that no taxis would stop in the bus lanes.

4.5.4 Scenario 4 (Share)

This scenario takes a more pragmatic approach by permitting taxis to use either general or BRT lanes. In the simulation taxi drivers choose their lane so as to minimise their expected travel times, which is a reasonable assumption. The only limitation is that taxis may only switch between BRT and general lanes at intersections since the barrier kerbs prevent lane changes mid-block. It is expected that taxis that travel the entire section will tend to use the bus lanes as express lanes, while those that overlap the section only partially may stay in general lanes to avoid the additional delays of navigating to the bus lanes (noting that this may require several lane changes). The choice of lane will however be sensitive to the levels of congestion in the general lanes and interference between bus and taxis in the bus lanes.

5 RESULTS

Results are presented in terms of vehicle volumes, passenger travel times, and queue lengths for the four scenarios. An additional sensitivity analysis is performed to test future growth scenarios.

5.1 Vehicle volumes

Table 2 indicates the private vehicle, taxi and bus volumes during the simulation period for the four different scenarios. Of most interest is scenario 4, where the simulation predicted about 70% of taxis would switch to bus lanes, and the remainder stay in the general lanes.

Table 2: Simulated traffic volumes by mode (veh/hr/direction)

		Scenario 1, 3 and 4		Scenario 2	
Time	PV	Taxi	bus	Taxi	bus
6-7	1477	79	9	0	25
7-8	1965	53	8	0	19
8-9	1861	56	4	0	15
9-10	1473	42	4	0	12
10-11	1364	48	4	0	14
11-12	1479	55	4	0	15
12-13	1513	61	4	0	16
13-14	1389	74	4	0	19
14-15	1432	86	4	0	21
15-16	1474	94	8	0	27
16-17	1549	85	9	0	26
17-18	1449	70	2	0	16

5.2 Passenger Travel Times

For the 12-hour simulations the mean travel time across all passengers was calculated, assuming an average occupancy of 75 passengers per bus, 15 per taxi, and 1.5 per car. These occupancies correspond to the maximum capacity of each mode, as actual occupancies could not be observed. Mean, minimum and maximum travel times (across all simulation runs) are shown in figures 7-10, as multiples of the free-flow travel time. Only the westbound direction is shown, as this was the most critical direction. The level of service was calculated in VISSIM by using the Highway Capacity Manual’s LOS definitions. The LOS is valid for urban arterials but not particularly for public transport routes and is therefore just for comparative purposes. The LOS is calculated for the general lanes and the BRT lanes and indicated on the graphs. The delay due to stopping and boarding of taxis was not included in the analysis.

5.2.1 Scenario 1 (Benchmark)

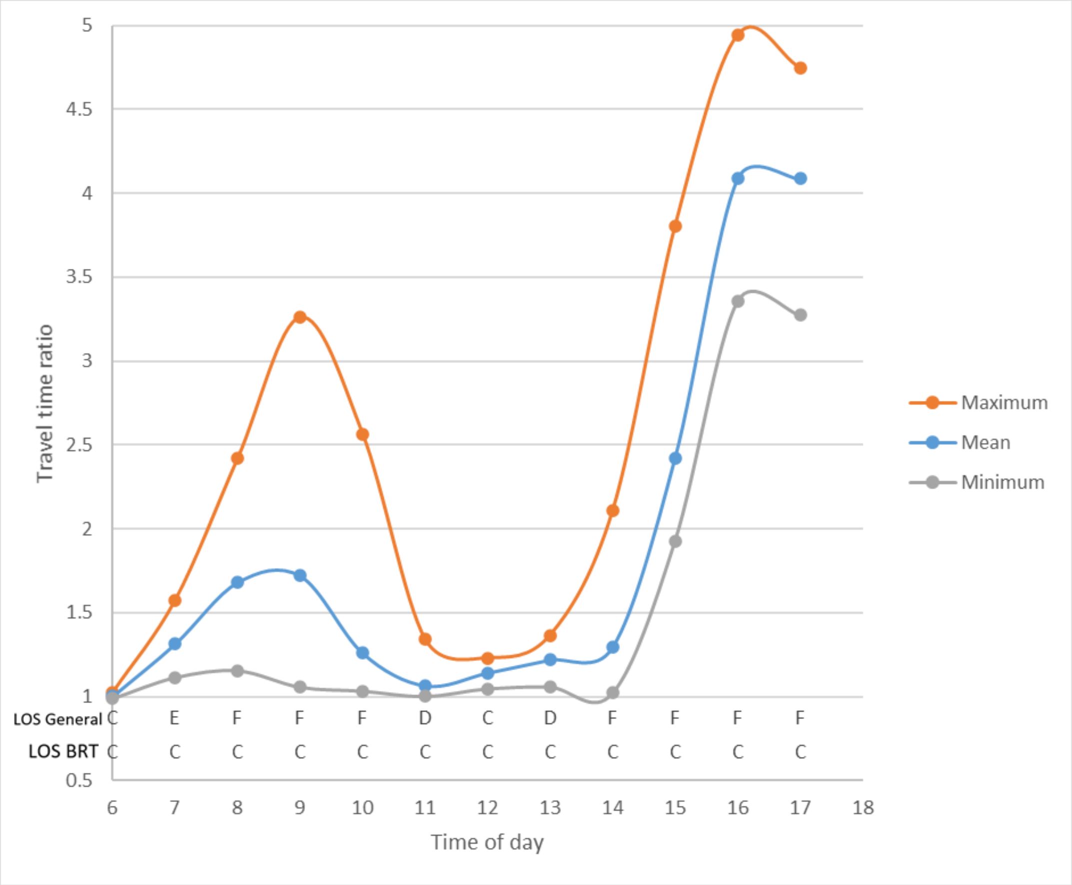

Figure 7: Scenario 1 westbound travel times and Level of Service (Travel time ratio is modelled divided by free-flow travel time)

The current scenario displays large random variations in travel times (Figure 7) in the westbound direction, especially during the peak periods. This is largely attributed to the lack of signal coordination, which introduces large random variations in queues depending on the random arrival and dispersion of platoons. This is consistent with the unstable traffic conditions experienced in general traffic lanes during these times, when congestion sets in and LOS F prevails. The congestion was however limited to the general lanes with travel times in the bus lanes never exceeding 290 seconds (including the time stopped at bus stations).

5.2.2 Scenario 2 (Remove)

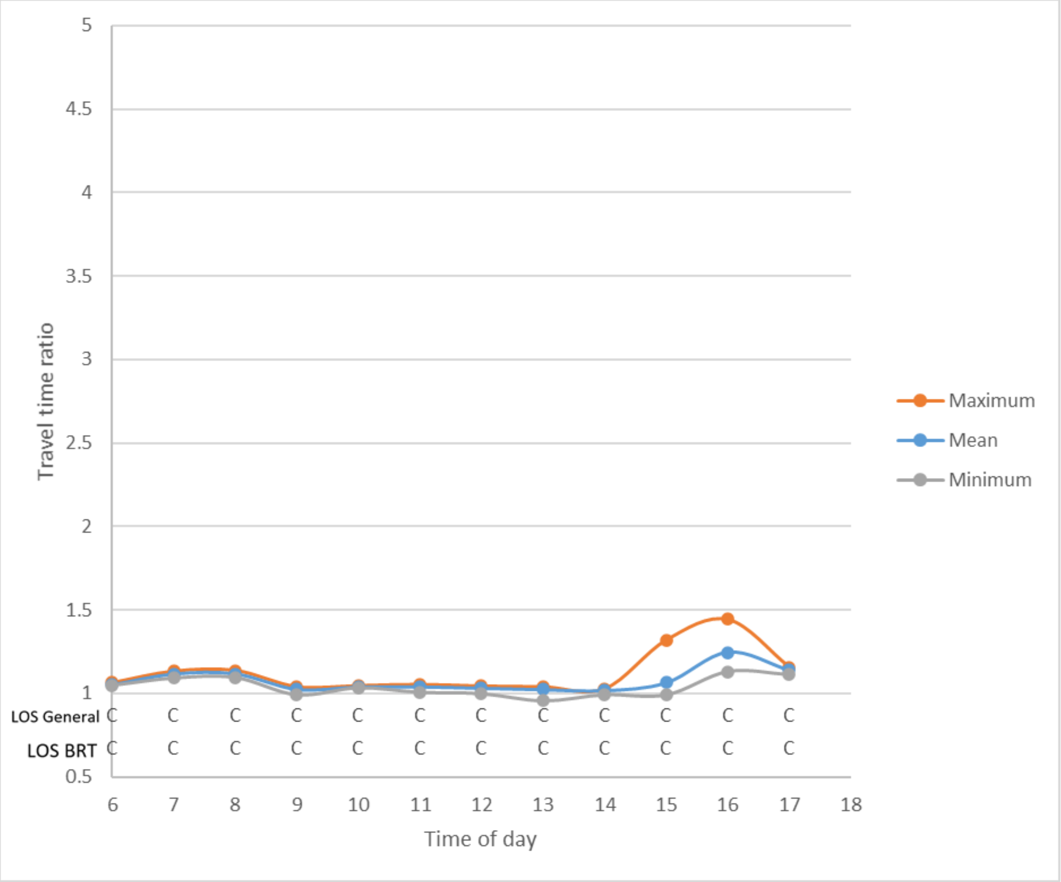

Figure 8: Scenario 2 westbound travel times and Level of Service (Travel time ratio is modelled divided by free-flow travel time)

For the *Remove* scenario mean passenger travel times are consistently lower than for the benchmark (Figure 8). Travel times vary minimally across the day, and the LOS remains at C, despite a small peak in the afternoon. This indicates that removing the taxis from the network alleviates congestion for the general lanes while the BRT lanes remain uncongested. There is spare capacity in the BRT lanes which can be utilised by increasing bus volumes in the BRT lanes.

5.2.3 Scenario 3 (Shift)

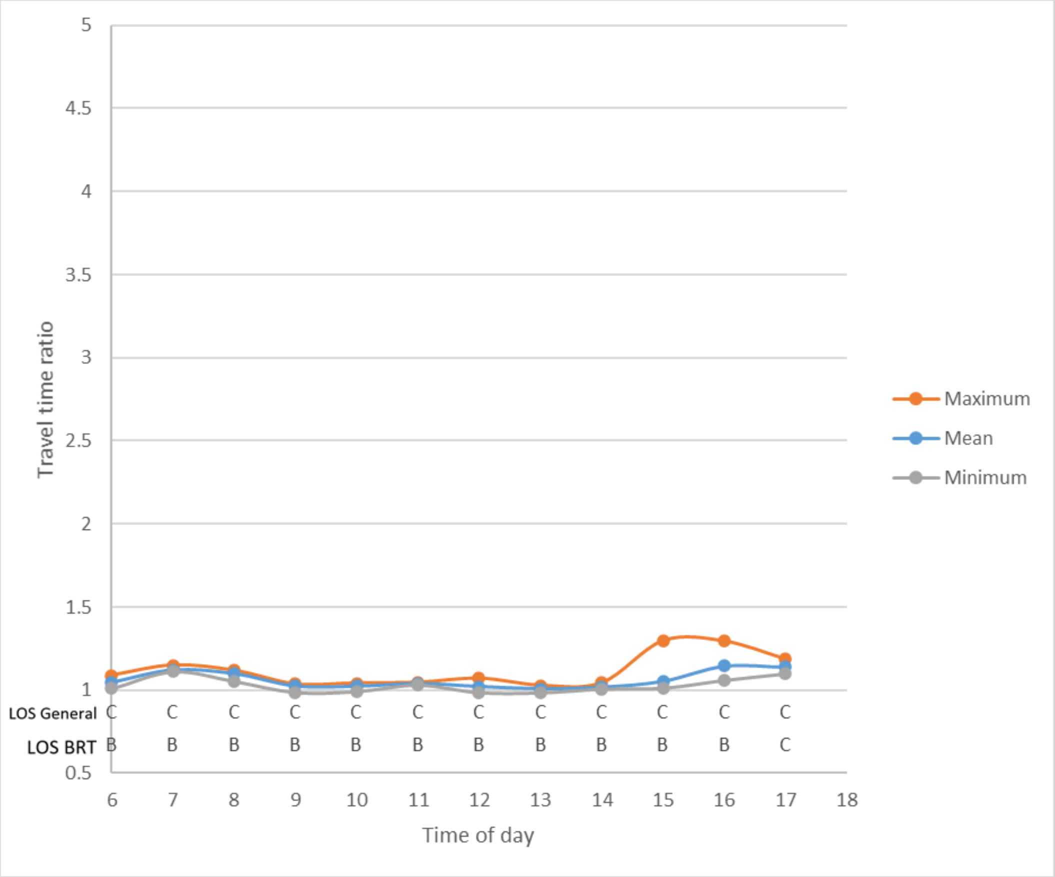

Figure 9: Scenario 3 westbound travel times and Level of Service (Travel time ratio is modelled divided by free-flow travel time)

The results for the *Shift* scenario (Figure 9) are similar, with average travel times and LOS remaining close to the minimum through-out the day. Conditions in the general lanes are identical to those for Scenario 2 as taxis are simply removed. Unexpectedly, the LOS in the BRT lanes improves from C to B for all but the final hour, even though vehicle volumes increase by the amount of taxis shifted to this lane. This is due to the fact that taxis travel faster in BRT lanes than buses as they do not stop, while in Scenario 2 all taxi passengers experience additional delay in BRT buses at stations. In some instances, the taxis are fast enough to travel through two green phases at successive intersections without stopping while the buses stop at one or both intersections. Important to note that taxi volumes are low enough not to congest the BRT lanes, so the impact on BRT passengers is negligible. There is currently spare capacity in the BRT lanes even if the taxis are moved to them.

5.2.4 Scenario 4 (Share)

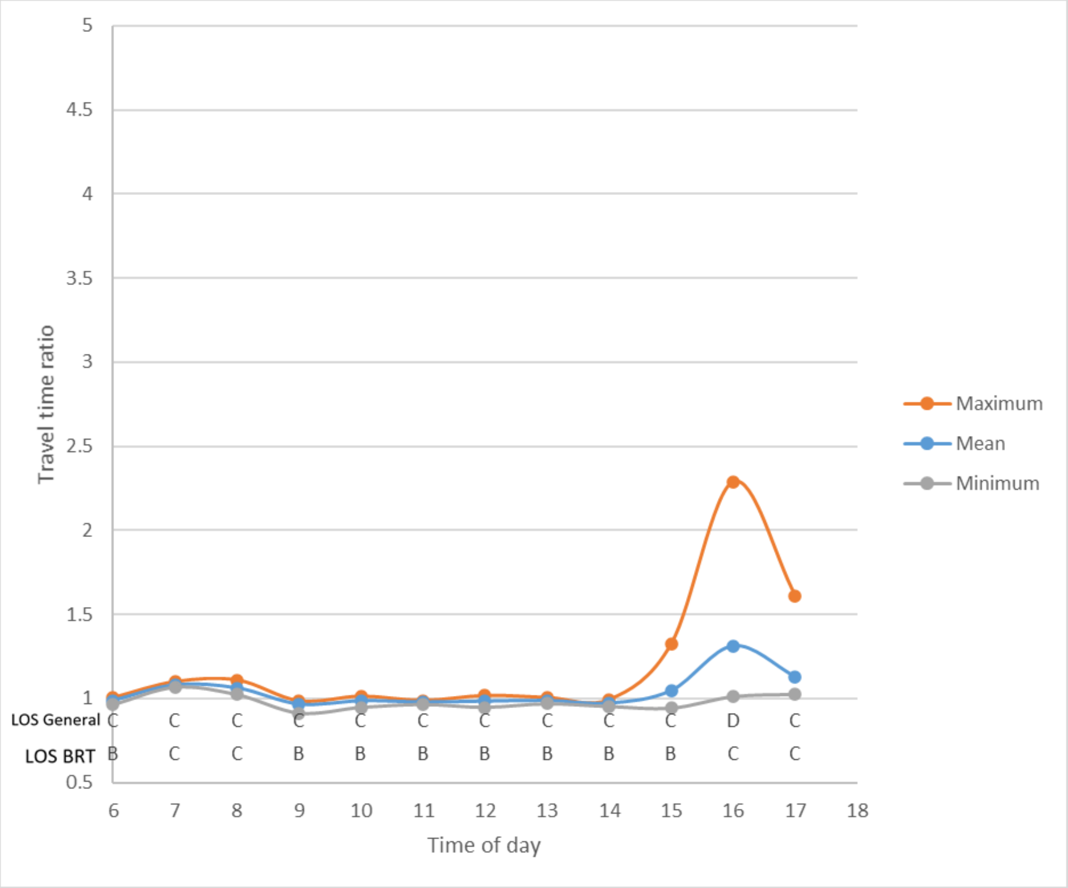

Figure 10: Scenario 4 westbound travel times and Level of Service (Travel time ratio is modelled divided by free-flow travel time)

This scenario is expected to perform somewhere between the *Benchmark* and *Shift* scenarios, as only some taxis move over to the BRT lanes. As expected, the results (Figure 10) vary by time of day. During the morning peak and midday period (up to 14:00) mean travel times and LOS are similar to the *Shift* scenario, with minimal congestion in either general or BRT lanes. Once again, the option of using the underutilised BRT lanes provides significant benefits to taxis and private vehicles. However, as volumes rise during the PM peak conditions deteriorate in both the general and BRT lanes, although they are still better than for scenario 1. With only 70% of taxis now using BRT lanes to avoid congestion in the general lanes, the LOS in the bus lanes is on average lower than in scenario 3, but by a small margin. Significant benefits accrue to all road users under this scenario.

5.3 Queues

Queue lengths are important as long queues formed by taxis in bus lanes may block buses and affect BRT operations. Figures 11 and 12 show queue lengths simulated for all four scenarios and averaged across the five key intersections in the experimental section.

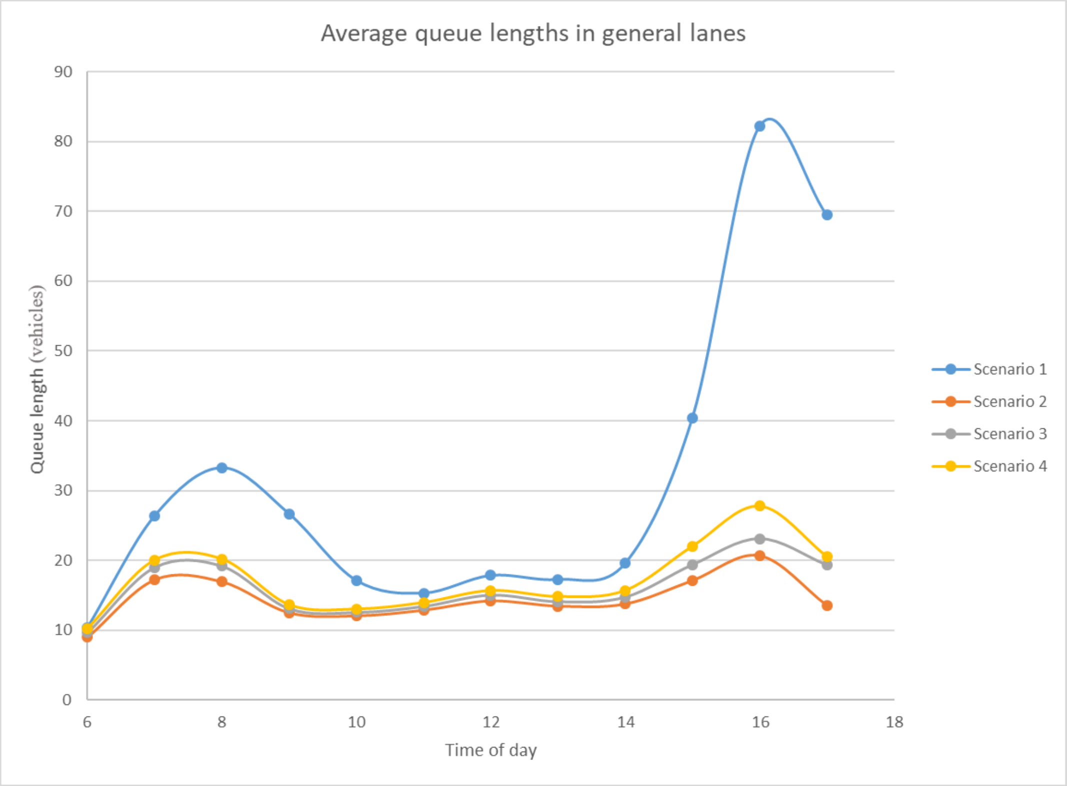

Figure 11: General lanes queue lengths, averaged across key intersections

The results largely mirror those from the travel time measures. In the general lanes average queue lengths are the highest for scenario 1 and the lowest for scenario 2, with scenario 3 and 4 performing similar (but slightly higher) than scenario 2. The average queue lengths during peak periods increase drastically in scenario 1 while the effect is less pronounced for the remaining scenarios. The average queue lengths recorded are proportional to the volume of traffic in the general lanes. As the taxis are removed from the general lanes the average queue lengths decrease.

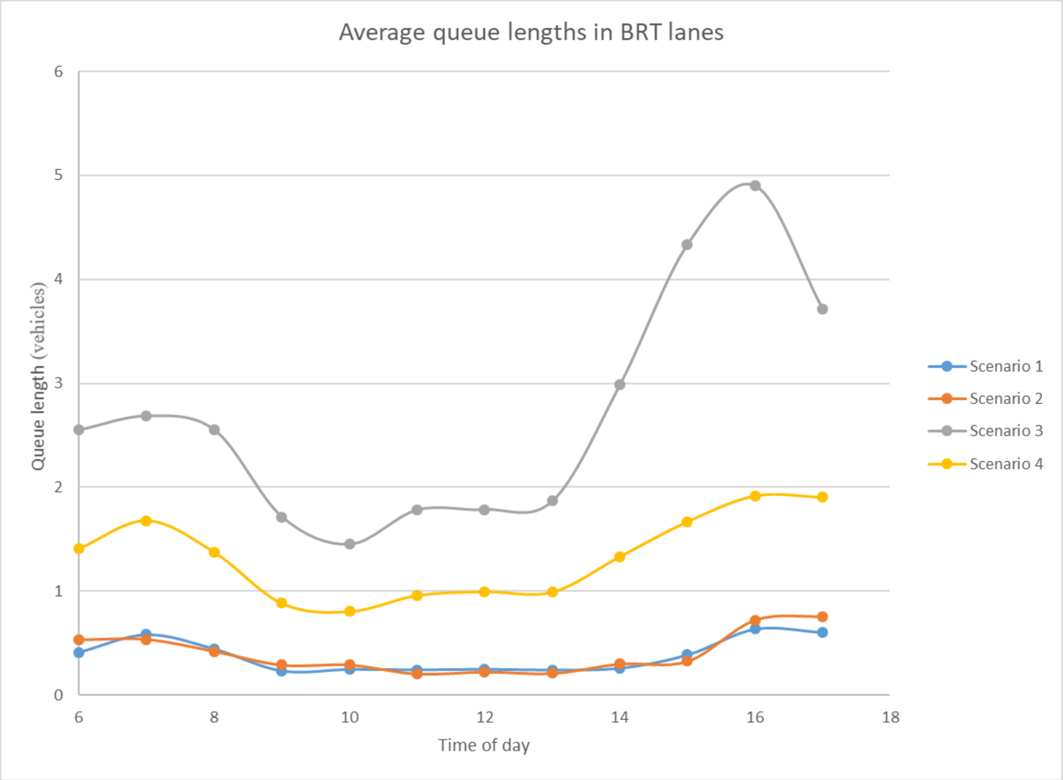

Figure 12: BRT lanes queue lengths, averaged across key intersections

In the BRT lanes queue lengths are directly proportional to the number of taxis using the lanes. Scenario 1 and 2 have no taxis traveling in the BRT lanes and subsequently have queue lengths of between 0 and 1 vehicles. Scenario 3 has the highest volume of taxis and the highest queue lengths which range from 1.5 to 5 vehicles. For scenario 4 average queues never exceed 2. During the analysis it was observed that taxis travelling in bus lanes created queue lengths long enough to reach bus platforms. These queues dissipated very quickly, and no instances of busses being delayed were observed. However increased taxi volumes would exacerbate the situation which may lead to buses being unable to reach platforms which would create delays in BRT lanes.

5.4 Sensitivity analysis

The foregoing showed that significant reductions in travel times are attainable for both private car users and public transport (specifically minibus-taxi) passengers by operating the bus lanes as shared or hybrid lanes allowing taxis to use them. However, this is predicated on both low current bus volumes (causing huge underutilisation of the bus lane infrastructure), and moderate taxi volumes (which are not enough to congest the bus lanes when switching over). The obvious question is whether these benefits would persist as public transport volumes rise.

To answer this question a sensitivity analysis was performed where bus and taxi volumes were increased to reflect the following assumptions:

- Case A: Current taxi and bus volumes apply (except for scenario 2 where taxis are removed)
- Case B: Taxi volumes are reduced by 50% and bus volumes increased by 100%. This represents a policy scenario where government succeeds partially in replacing informal operators with formal bus services. Total public transport demand remains unchanged.
- Case C: Both taxi and bus volumes increase by 40% from current levels. This is to take account of the demand effect from a long-term growth in public transport demand, as well as a possible short-term latent demand effect where ridership grows as congestion is relieved. Apart from the improvement in taxi operating speeds under a hybrid scenario, a general upliftment of the quality of taxi services envisioned by government might contribute to greater attractiveness of this mode. The 40% rise is consistent with the difference in overall volumes between the AM and PM peaks, and could therefore result if demand were to shift away from parallel routes to this corridor in the AM peak.

Table 3 summarises the vehicle volumes for each case.

Table 3: Vehicle volumes (veh/hour) used as comparison cases for sensitivity analysis

Case A	Case B	Case C
Bus =14 Taxi=147	Bus =29 Taxi=74	Bus=20 Taxi=206

The comparison was only done for the AM peak period (7:15 to 8:15) and for the westbound direction as these are more critical. Figure 13 shows the results by mode, using box plots to visualise the variability across the ten simulation runs of each scenario and case.

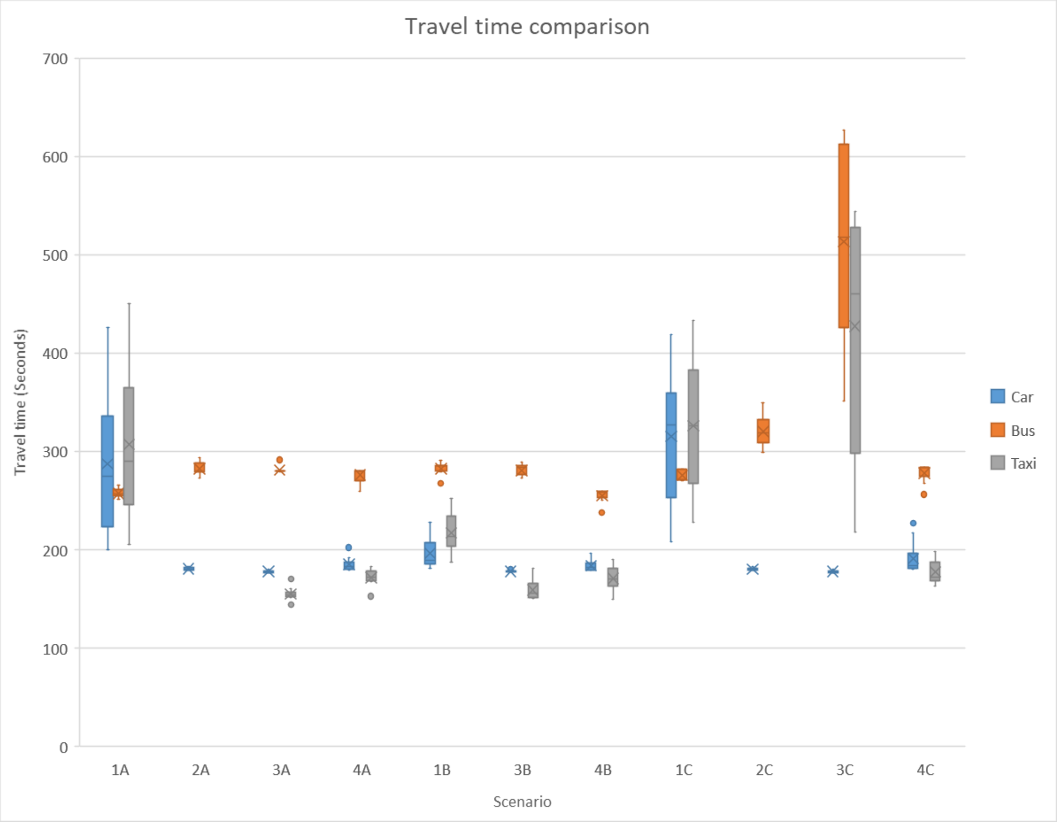

Figure 13: Westbound travel time comparison (sensitivity analysis; see text for description of cases). Box plots show from bottom to top: minimum, 1st quartile, mean, 3rd quartile and maximum values

The results confirm that under current public transport demand (case A) the *Shift* scenario (3) produces the lowest travel times for cars, buses and taxis. Scenario 3 is however sensitive to changes in public transport demand. Should demand shift from taxis to buses (case B), scenario 4 performs slightly better as bus travel times drop by 2% (due to the reduction of taxi volumes in the bus lanes), even though taxi times rise slightly. Should overall public transport volumes rise (case C), it is clear that the *Shift* scenario exceeds its capacity as significant congestion sets in in the bus lanes (see 3C in Figure 13). This raises travel times for both taxi and bus passengers by a factor of 2 or more. It is clearly not viable to accommodate even moderately high volumes of taxis exclusively in bus lanes, even at these low bus volumes.

For case C the best solution is the *Share* scenario (4C), where excess taxis can also use general lanes and a user equilibrium can be expected to result between bus and general lanes[2]. Even at these elevated demand levels, overall capacity is sufficient to accommodate all vehicles without excessive delay; the share scenario distributes road capacity more efficiently between modes. Compared to the current lane allocation (1C), *Share* would also lead to dramatic improvements in travel time reliability, as can be seen from the much

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[2] Under Scenario 4 taxi travel times should equalise between bus and general lanes, even though bus travel times are still higher due to stopping delay at stations.

smaller variations in travel times (58% reduction in standard deviation). Bus reliability remains unchanged, but both taxi and car users would benefit from more predictable travel times.

6 CONCLUSIONS: TOWARDS SHARED INFRASTRUCTURE IN HYBRID SYSTEMS

The study uses a simulation-based approach to examine the implications of mixing informal and formal operations in a hybrid public transport system, based on a real-world Bus Rapid Transit service. The focus is exclusively on demand and capacity considerations, taking the interactions between minibus-taxis, cars and buses into account. But the study is in two senses an ideal case: firstly, taxis operate in express mode with minimal stopping along the test section; secondly, bus infrastructure is ample, with bypass-lanes at all stations and two discharge lanes at intersections downstream from stations. This reduces the possibility for interference between minibuses and buses when sharing BRT lanes.

The results indicate that the potential benefits of shared infrastructure vary significantly across the day, depending on traffic conditions in both general and bus lanes. Under uncongested conditions, the present approach – dedicating bus lanes for BRT and restricting minibuses to general lanes – is best, as there is little benefit gained from hybrid operations. However, as taxi and car volumes grow and congestion sets in during peak periods, there is a clear case to be made for allowing taxis to share bus lanes in order to make use of excess capacity there. Even at the modest taxi volumes currently seen in this corridor, taxis contribute significantly to congestion in general lanes, and removing them reduces demand to below capacity, leading to significant savings for private vehicle users (scenarios 3A and 4A). Taxi passengers also benefit through a 50% reduction in travel time on average in the bus lanes, while total bus lane volumes remain below capacity. The impact on buses is minimal.

These results are of course predicated on relatively low bus frequencies (on average 14 buses per hour in the bus lanes), which is typical of BRT systems in South Africa and elsewhere where BRT demand is much lower than in many cities in Latin America and Asia (Scorcia and Munoz-Raskin, 2019; Hensher and Golob, 2008). The excess capacity is significant and can be put to better use in the short term.

The above results persist even when taxi and bus volumes are increased to take account of demand growth and latent demand. But the rules of sharing infrastructure now become critical. If all taxis are forced into bus lanes without the option of using general lanes, their capacity is exceeded, and conditions deteriorate significantly for all public transport users (Scenario 3D). But if taxi drivers are given a choice of whether to use general or bus lanes, uncongested flow returns due to the spread of taxis between the two lane types (Scenario

4D). We predict up to a 30:70 split of taxis between general and bus lanes for the simulated case, although in general this number would be sensitive to bus and car volumes and the details of taxi routing along the corridor. Overall, the more permissive approach towards which lanes taxis can use is not only more efficient but also more implementable as it requires less enforcement.

What do these results suggest for public transport planning? It is clearly not optimal, from an operational point of view, to implement exclusive infrastructure under conditions of low bus demand, such as in the case of Tshwane. If it is argued that the long-term strategy is to expand the BRT system, excess bus lane capacity might only be temporary, and be put to better use as future routes are added and/or frequencies grow. However, the experience in South Africa has demonstrated the significant risks attached to this argument if network expansion is delayed due to problems in dealing with informal incumbents, and fiscal constraints (Manuel and Behrens, 2018). In this case the extra costs of sub-optimal performance might be high, and even perversely delay further upgrading as negative political and public perceptions lead to questioning of the entire sustainable mobility project. The long-term setback for the public transport agenda might be severe.

An alternative approach might be to rethink the BRT project itself and create a transitional approach that relies on dedicated infrastructure shared by all qualifying public transport operators, formal and informal, for a period of time. This will demonstrate the intention of giving priority to public transport, while spreading benefits much more widely than with bus-only systems. The greater efficiency gained by informal operators may incentivise them to invest in larger vehicles, and gradually become more compatible with buses within a hybrid framework. Performance in the shared lanes should be closely monitored to prevent congestion, perhaps adjusting the rules for lane admission and use as needed. In the longer run, it seems feasible that such shared lanes may graduate to full bus lanes, as demanded by actual passenger volumes and evolving network needs.

The study does not conclude that it is advisable to allow informal vehicles in *existing* bus lanes. Present design of lanes and stations are not suited to hybrid operations, and much further research is needed on operational aspects of shared infrastructure. Specific focus is needed on (re)designing the infrastructure to accommodate hybrid operations in a safe manner, as more complex stopping manoeuvres by vehicles of different sizes could create challenges for the safety of pedestrians and passengers. Furthermore, allowing taxis into bus lanes without an industry-agreed plan as to its objectives, management, and enforcement could endanger its effectiveness, while bestowing on informal operators a perceived right to access that could be hard to retract.

Further research is needed on the transferability of these results to different operating environments, including corridors with different demand and operational conditions, longer lengths, and more restrictive infrastructure. For instance, the absence of bypass lanes at stations will significantly increase interference between informal and formal vehicles, and probably preclude any sharing of infrastructure. The results would also be sensitive to taxi stopping patterns, and the design of safe loading and unloading facilities for smaller vehicles in exclusive lanes needs attention. Future models should model physical stopping and boarding of paratransit vehicles in BRT lanes more accurately. The use of advanced signal strategies to promote orderly shared operations should also be investigated.

Lastly, in terms of research methods, the paper demonstrated that a microsimulation model can be calibrated to produce a believable representation of minibus-taxi behaviour in mixed traffic. Informal industry drivers display more aggressive braking behaviour, but acceleration and speed characteristics are constrained by vehicle properties and traffic conditions, to be largely similar to other vehicles'. Further work is however needed to calibrate driving and lane changing behaviour models for informal drivers in different contexts, in order to strengthen researchers' ability to assess the efficacy of alternative approaches towards upgrading this important mode of transport in cities of the global south.

7 ACKNOWLEDGEMENTS

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APPENDIX A- Input parameters

	Input parameter	Input value
1.	Speed Limit	60 km/h
2.	Dwell times (taxis)	0-30 sec; Avg. 9.57 sec; std. dev. 5.9 sec
3.	Dwell time (buses)	0-130 sec; Avg. 30 sec; std. dev. 10 sec
4.	Acceleration (Buses)	Lower=0.22; mean=1.08; Upper=2.15 (m/s^2)
5.	Acceleration (Cars)	Lower=0.33; mean=1.76; Upper=3.99 (m/s^2)
6.	Acceleration (Taxis)	Lower=0.1; mean=1.02; Upper=2.1 (m/s^2)
7.	Deceleration (Buses)	Lower=-0.13; mean=-1.34; Upper=-3.05 (m/s^2)
8.	Deceleration (Cars)	Lower=-0.18; mean=-1.9; Upper=-3.77 (m/s^2)
9.	Deceleration (Taxis)	Lower=-0.1; mean=-1.24; Upper=-3.1 (m/s^2)
10.	Desired Speeds (Bus)	Lower=13.7; upper=42 (km/h)
11.	Desired Speeds (Car)	Lower=13.7; upper=45.2 (km/h)
12.	Desired Speeds (Taxis)	Lower=13.7; upper=50.2 (km/h)
13.	Paul Kruger Intersection (Peak volume)	AM=3847; Mid=3330; PM=3915 (Veh/hour)
14.	Andries Intersection (Peak volume)	AM=4109; Mid=3752; PM=3846 (Veh/hour)
15.	Lilian Ngoyi Intersection (Peak volume)	AM=4300; Mid=3344; PM=3892 (Veh/hour)
16.	Sisulu Intersection (Peak volume)	AM=3604; Mid=3115; PM=4053 (Veh/hour)
17.	Kotze Intersection (Peak volume)	AM=2395; Mid=2053; PM=2461 (Veh/hour)
18.	Du-Toit Intersection (Peak volume)	AM=1106; Mid=1010; PM=1127 (Veh/hour)
19.	Nelson Mandela Intersection (Peak volume)	AM=1950; Mid=1563; PM=2021 (Veh/hour)
20.	Weidemann 74 Vehicle following parameters (general traffic)-Stand still distance	1.2 meters
21.	Weidemann 74 Vehicle following parameters (general traffic)-Additive factor	2.9
22.	Weidemann 74 Vehicle following parameters (general traffic)-Multiplicative factor	2

APPENDIX B- Estimation of excess capacity in bus lane

1) Capacity of BRT Station (ITDP, 2017)

$$station\ capacity = \frac{Nsp.X.3600}{Td.(1 - Dir)}[\frac{buses}{hour}]$$

Where:

Nsp= Number of stopping bays=2
X= Max saturation level=0.4
Td= dwell time=30 seconds
Dir=percentage of limited-stop vehicles=0

So: Station capacity=96 buses/hour
Current peak-hour bus volume = 9 buses/hour/direction
Excess (unused) capacity= 87/96=90.6%

2) Capacity of bus lanes

Assume critical element is at intersections

$$Intersection\ capacity = \frac{g_b.s_b.n_b}{C}[\frac{buses}{hour}]$$

Where:

g_b= Green time for buses=29 sec
C= Cycle length=90 sec
s_b= Saturation flow rate (buses)=720 veh/h (ITDP, 2017)
n_b=Number of bus lanes= 1 per direction

So: Capacity= 232 buses/hour/direction

Thus, excess capacity = 232-9= 223 buses/hour, or $\frac{223}{232} = 96.1\%$

Or, assuming 9 buses/hour and vehicle equivalency of 1.5 taxis/bus (TRB, 2000). Lane can accommodate additional (232-9)*1.5=334 taxis/hour.